December 1982 A.E. Res. 82-46

THE VALUE OF ECONOMIC THRESHOLDS FOR MANAGING AGRICULTURAL PESTS

G.R. Fohner
G.B. White
S.J. Schwager

Department of Agricultural Economics
Cornell University Agricultural Experiment Station
New York State College of Agriculture and Life Sciences
A Statutory College of the State University
Cornell University, Ithaca, New York 14853

It is the policy of Cornell University actively to support equality of educational and employment opportunity. No person shall be denied admission to any educational program or activity or be denied employment on the basis of any legally prohibited discrimination involving, but not limited to, such factors as race, color, creed, religion, national or ethnic origin, sex, age or handicap. The University is committed to the maintenance of affirmative action programs which will assure the continuation of such equality of opportunity.

ABSTRACT

Economic thresholds may increase net revenue to farmers and reduce environmental costs of pesticides by indicating when pest densities warrant control. The use of economic thresholds, however, requires information about pest density and the relationship between that density and the value of the crop. The field sampling and research for acquiring this necessary information both have costs, and an important question for evaluating an economic threshold for a particular pest is whether the costs of developing and using the threshold decision rule exceed the benefits. The objectives of this study were to describe the characteristics of pest problems that most affect the value of economic thresholds, indicate the types of pest problems for which the thresholds are potentially most valuable, and determine the quality of information needed to fulfill that potential.

A mathematical model and Monte Carlo simulation were used to compare the costs of pesticide and crop loss using economic thresholds, routine application of pesticide, and no applications. This comparison was made for a range of alternative assumptions about five factors:

1. The magnitude and variability of pest density among fields and growing seasons,

2. the function relating pest density and expected crop loss,

3. the variability in the effect of pest density on crop loss,

4. the effectiveness with which pesticide prevents crop loss, and

5. the accuracy of the decision maker's information about pest density and the relationship between pest density and crop loss.

The performance of the economic threshold depended primarily on the magnitude and variability of pest density. Economic thresholds were most valuable when pest densities both well above and well below the threshold were likely to occur. While this variability in pest density favored the use of economic thresholds, variability in crop losses for particular pest densities was unfavorable because it reduced the predictability of crop loss based on estimated density. The value of increasing the accuracy of the estimated threshold depended on the magnitude and variability of pest density and the slope of the function relating pest density and expected crop loss. Thresholds based on estimates of crop loss within 20 percent of the true average loss generally performed nearly as well as the true economic threshold. When sample counts were assumed to be errorless, and the spatial distribution of the pest in the field was negative binomial, the value of using the economic threshold was not increased substantially by sampling 60 instead of 30 plants.

The concepts, methods, and results of this study may contribute to pest management programs in three ways: 1) as a conceptual framework illustrating the interdependencies among decision rules, sampling procedures, quality of information, and characteristics of pests and crops in determining the value of economic thresholds; 2) for classifying pest problems according to suitability for economic thresholds; and 3) for selecting decision rules, sampling procedures, and setting research priorities.

ACKNOWLEDGMENTS

The authors gratefully acknowledge assistance from B.F. Stanton, whose careful reading and constructive comments on the initial draft of this report greatly improved the presentation.

This study was supported by funds provided under Hatch project NY(C)-121416.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

THE VALUE OF ECONOMIC THRESHOLDS FOR MANAGING AGRICULTURAL PESTS

by

G.R. Fohner, G.B. White, and S.J. Schwager*

I. INTRODUCTION

The economic threshold for an agricultural pest is the pest density at which the cost of reducing the density equals the expected increase in crop value from that reduction (Headley; Stern et al.). At pest densities below the threshold, the cost of reducing density exceeds the expected increase in crop value; at densities above the threshold, the cost of reducing density is less than the expected increase in crop value. This economic threshold concept formalizes the principle that pests should be tolerated when expected losses are less than the additional costs of controlling the pest. This principle is fundamental to integrated pest management (Apple et al.; Flint and van den Bosch; Huffaker) because tolerance of low pest densities allows use of management practices that are more diverse and less costly than those needed to eradicate pests.

In addition to its importance as a concept supporting integrated pest management, the economic threshold has been used widely in practice to decide whether pest densities warrant control (Boethel and Eikenbary; California Agriculture; Sterling; Westigard). Ideally, the use of economic thresholds as decision rules increases net revenue to farmers by indicating when pest control measures are justified economically. The use of economic thresholds, however, requires estimates of pest density and knowledge of the relationship between that density and the value of the crop. The field sampling and research for acquiring this necessary information both have costs, including direct expenditures and opportunity costs of foregoing other managerial and research activities. An important question for evaluating an economic threshold for a particular pest problem is whether the costs of developing and using the threshold decision rule exceed the benefits. This question is analogous to one posed by Havlicek and Seagraves concerning the value of information for improving the use of fertilizer. As in their analysis, the value of a threshold decision rule can be assessed by comparing net revenue when pest management decisions are made with the rule and net revenue when decisions are made without it. Since pest management tactics such as pesticides may have external costs not reflected in net revenue to individual farmers, these costs should also be included in the comparison.

The objective of this study was to describe the characteristics of pest problems that most affect the value of threshold decision rules for deciding whether or not to apply a pesticide. This objective included describing the relationship between the value of a threshold decision rule and the quality of the information used to develop and use the rule. The results of the

*Research Associate and Assistant Professor, Department of Agricultural Economics; Assistant Professor, Department of Plant Breeding and Biometry; Cornell University, Ithaca, New York, 14853-0398.

study indicate the types of pest problems for which the threshold decision rule is potentially most valuable, and the quality of information needed to fulfill that potential.

II. A MODEL FOR EVALUATING THRESHOLD DECISION RULES

2.1 Factors Affecting the Value of Threshold Decision Rules

A threshold decision rule can minimize the combined cost of pesticide and crop loss by indicating correctly whether pesticide should be applied. The rule may lead to an incorrect decision that fails to minimize cost for three reasons: 1) actual and estimated pest densities may be on opposite sides of the threshold; 2) the threshold used in the decision may misrepresent the true relationship between pest density and crop loss; and 3) variability in crop value and in the effect of pest density on the crop may result in lower or higher cost of crop loss than expected.

The value of a threshold decision rule (AT) depends on its success minimizing cost and on the difference between that minimum cost and the cost using other decision rules such as routine application of pesticide (AR) and no applications (AN). In this study, a mathematical model was used to examine the effects of five factors on the value of using AT instead of AR or AN. These five factors were:

1. the magnitude and variability of pest density among fields and growing seasons,

2. the function relating pest density and expected crop loss,

3. the variability in the effect of pest density on crop loss,

4. the effectiveness with which pesticide prevents crop loss, and

5. the accuracy of the decision maker's information about pest density and the relationship between pest density and crop loss.

The mathematical model incorporated alternative assumptions about these five factors. For each set of assumptions, the performances of the three decision rules (AT, AR, and AN) were compared in terms of the combined cost of pesticide and crop loss. Also, the number of pesticide applications using AT was evaluated to gauge the potential effect of the threshold rule on long-run and external costs from pesticides, such as potential effects on health, environment, and agricultural productivity.

Since some factors were represented in the model with probability distributions, the performance of each decision rule varied with the values randomly selected from those distributions. Analytical derivation of the mean, variance, and quantiles of cost for the threshold rule was intractable, so these parameters were estimated using Monte Carlo simulation (Hammersley and Handscomb, Naylor, Shannon). To provide precision in the comparison of decision rules, 400 replications were performed for each model specification and decision rule.

2.2 Description of the Model

The model used to compare decision rules generated values for actual pest density, estimated density, crop loss, and costs with and without pesticide for each replication (Figure 1). For the threshold decision rule, the decision whether or not to apply pesticide was based on an estimate of pest density. If the estimated density based on sampling was less than the predetermined threshold, pesticide was not applied, and cost equaled the crop loss resulting from the pest. If the estimated density exceeded the threshold, pesticide was applied and crop loss to the pest was reduced, so cost equaled the cost of pesticide application plus a partial crop loss to the pest.

2.3 Specification of the Model

2.3.1 Distribution of Pest Density

Pest density, the average number of pests per plant in a field, was assumed to be a random variable having a gamma distribution.[1] To study the effect of the magnitude and variance of pest density on the performance of the threshold decision rule, five different gamma distributions were used in the experiment (Figure 1 and Table 1). An indication of the shapes of the gamma distributions used in this study is provided by the frequency distributions of observed values drawn from those distributions (Appendix C, Figure C1).

2.3.2 Loss Functions Relating Pest Density and Crop Loss

The relationship between the pest density in a field and the crop loss resulting from the pest was represented in this experiment by loss functions with two components: 1) an expected or average loss resulting from a particular pest density, and 2) variability in loss due to other variables, such as weather, crop condition, crop prices, and spatial distribution of the pest, that interact with pest density to determine loss to the pest. These two components were specified to vary independently. Four loss functions were used in this experiment (Figure 1 and Table 2). Loss functions 1, 2, and 3 (LF1, LF2, and LF3) had a linear functional form for average loss, and loss function 4 (LF4) had an exponential form. The exponential form implied a larger difference in crop loss between low and high pest densities than was implied by the linear form. Loss functions LF1, LF2, and LF4 had additive variability terms, and LF3 had a multiplicative variability term. The multiplicative term implied that the variability in crop loss resulting from a particular density was larger for high densities than low. Of the additive loss functions, LF1 had less variability in loss for a particular pest density than LF2 and LF4, which had the same variability term.

Both functional forms for average loss were specified so that when the average number of pests per plant in the field was five, the expected loss

---

[1] Gamma distributions are a family of continuous probability distributions that includes exponential and chi-square distributions as special cases (Mood, Graybill, and Boes). Individual gamma distributions can be described by two parameters, one for shape and one for scale. For a variable having a gamma distribution, only values greater than zero can occur.

$W_1 \sim N(0,9.37)$

$2W_1 \sim N(0,37.45)$

$W_2 \sim LN(1,.5828)$

Pest Density X

generated from specified gamma distribution

$\Gamma(2.8,.5)$

$\Gamma(1.18,.3246)$

$\Gamma(4.9,.6614)$

$\Gamma(2.8,.7363)$

or $\Gamma(2.8,.3146)$

Crop Loss Without Pesticide: $L(X,W) = \begin{cases} 1.2X + W_1 \\ 1.2X + 2W_1 \\ 1.2XW_2 \\ \text{or} \\ \exp(.4238X-.006922X^2)-1 + 2W_1 \end{cases}$

Sample Estimate of Pest Density

$\hat{X} = \text{count}/N$

$\text{count} \sim \text{Neg Bin}(N\cdot X, .5\cdot N)$

$N = 30$ or 60

Total Cost with Pesticide

$K = k' + F\cdot L(X,W)$

$= \begin{cases} \$6 \\ \text{or} \\ \$4.20 + F\cdot L(X,W) \end{cases}$

$F \sim \text{beta}(1.8,4.2)$

Compare $\hat{X}$ with Assumed Threshold $\hat{T}$ to Determine Cost

if $\hat{X}<\hat{T}$ cost $= L(X,W)$

if $\hat{X}\geq\hat{T}$ cost $= K$

Rule AT : $\hat{T} = (2.5, 4.0, 4.5, 5.0, 5.5, 6.0, 7.5, \text{ or } 10.0)$

Rule AR : $\hat{T}=0$ Rule AN : $\hat{T}=\infty$

Figure 1. Summary of the Model
(continued next page with description of variables)

X: actual average pest density per plant in the field

$\hat{X}$: estimated pest density based on sampling

W: variability in the effect of pest density X on loss L

L: loss function L(X,W), actual crop loss per acre due to the pest when actual pest density equals X and random variability equals W

k': per acre cost of applying pesticide

F: fraction of crop loss to the pest that occurs despite the pesticide application

K: total cost per acre when pesticide is applied; cost of pesticide application plus fractional crop loss

T: the true threshold pest density such that if $X > T$ then the expected loss without a pesticide application exceeds the expected cost with the application

$\hat{T}$: the threshold used to decide whether to apply pesticide

Figure 1 continued - Summary of the Model

TABLE 1

Gamma Distributions of Pest Density
Used in Simulation

Pest Distribution	Prob. of X > 5	Variance	Mean	Median	Shape Parameter	Scale Parameter
I	.50	11.20	5.60	5.0	2.80	.5000
II	.25	11.20	3.64	2.7	1.18	.3246
III	.75	11.20	7.41	6.9	4.90	.6614
IV	.25	5.17	3.80	3.4	2.80	7363
V	.75	28.29	8.90	7.9	2.80	.3146

	Low Variance	Moderate Variance	High Variance
Low Probability of (pest density > 5.0)	IV	II	
Moderate Probability of (pest density > 5.0)		I	
High Probability of (pest density > 5.0)		III	V

TABLE 2

Crop Loss Functions Used in Simulation

Loss Function: L(X,W)	Average Loss when Density = X	Variability in Loss
1) $1.2X + W_1$	$1.2X$	$W_1 \sim \text{Normal}(0,9.37)$
2) $1.2X + 2W_1$	$1.2X$	$2W_1 \sim \text{Normal}(0,37.45)$
3) $1.2XW_2$	$1.2X$	$W_2 \sim \text{Lognormal}(1,.583)$
4) $\exp(.4238X - .006922X^2)-1+ 2W_1$	$\exp(.4238X - .006922X^2)-1$	$2W_1 \sim \text{Normal}(0,37.45)$

was \$6 per acre. Accordingly, for the linear form, for which each incremental change in pest density resulted in the same change in crop loss, average crop loss was \$1.20 per pest per plant (X). For the exponential form, for which average loss equaled $(\exp(ax+bx^2)-1)$, the values of a and b were specified to be .4238 and -.006922. With these values, average loss was \$6 when average pest density was five, and loss grew larger at an increasing rate up to X = 22.1 and reached a maximum at X = 30.6. Of the 2,000 pest densities in this experiment (400 for each of five pest distributions), only seven exceeded 22.1 and only one slightly exceeded 30.6. Consequently, for the range of X values in this experiment the exponential loss function was characterized by average loss that grew larger at an increasing rate as pest density increased.

Two specifications of additive variability were used in the experiment. For these two specifications, crop loss from the pest equaled average loss for the pest density plus departure from average due to variability in the effect of the pest density. Each additive variability term was specified to have the same normal distribution for all pest densities. (The assumptions implicit in using the same distribution for all densities are discussed in Appendix A.) Normality was assumed because the variability term represented the combined effect of numerous unspecified factors that together might be expected to produce a normally distributed combined effect. The means of the two additive variability terms were specified to be zero, implying that the component of the loss function representing average loss included any net positive or negative effects of unspecified factors that might be correlated with pest density.

The variance of the additive variability term W_1 was specified to be 9.37, so that the 95 percent probability interval for crop loss was -\$6 to \$6 around average loss for the pest density.[2] Consequently, when pest density was five, crop loss was between \$0 and \$12 with probability .95. The variance of the other additive variability term $2W_1$ was 37.45, so the 95 percent probability interval for crop loss was -\$12 to \$12 around average loss for the pest density. With this variance, when pest density was five, crop loss was between -\$6 and \$18 with probability .95.

For the loss function (LF3) with multiplicative variability, crop loss from the pest equaled the product of the variability term and the average loss for the pest density, so the variability in the effect of the pest increased for higher pest densities. (The assumptions implicit in multiplicative variability are discussed in Appendix A.) The multiplicative variability term W_2 was assumed to have a lognormal distribution with mean equal to one, again implying that the average crop loss for a particular pest density equaled the average loss component of the loss function for that density. The variance of the multiplicative variability term was specified as .583, so that when pest density was five, crop loss was less than \$18 with probability .975, the same as with LF2. The magnitudes of variability for LF2 and LF3 were specified to be comparable when pest density was five so that differences in results for the two functions would more clearly reflect the differences in functional form rather than magnitude of variance.

---

[2] Some damage to foliage by pests may increase yield (Glass).

2.3.3 Total Cost When Pesticide is Applied

Total cost per acre when pesticide is applied was specified to have two components: the cost of the pesticide application and the cost of crop loss due to the pest despite the application. Two specifications were used in the experiment (Figure 1 and Table 3). In the first specification, a pesticide application costing \$6 per acre was assumed to prevent all crop loss to the pest, so the total cost was always \$6 when a pesticide was applied.

TABLE 3
Total Cost with Pesticide

Specification	Total Cost with Pesticide \$ per Acre	Cost of Pesticide \$ per Acre	Fractional Crop Loss
1) No Crop Loss with Pesticide	6.00	6.00	0
2) Variable Crop Loss with Pesticide	$4.20 + F \cdot L(X,W)$	4.20	$F \sim \text{beta}(1.8,4.2)$

In the second specification, the pesticide application cost \$4.20 per acre but did not prevent all crop loss, so total cost was \$4.20 plus a fractional crop loss. The fraction of crop loss that occurred despite the pesticide application was specified to vary between zero and one, having a beta distribution[3] with mean 0.3, mode 0.2, and variance 0.03 (thus with parameters equal to 1.8 and 4.2). The cost due to crop loss was the product of the variable fraction (F) and the crop loss (L) that would have occurred without the pesticide application. The values of F and L were specified to vary independently.

2.3.4 True and Assumed Economic Thresholds

The true economic threshold, which in practice is unknown, is here defined as the pest density at which the expected crop loss without the pesticide application equals the expected cost of crop loss and pesticide if pesticide is applied. At lower densities, the expected cost with the pesticide application exceeds the expected crop loss without it; at higher densities expected crop loss without pesticide application exceeds the expected cost with it. The loss functions and cost equations for pesticide applications were specified so that the true threshold was five pests per plant for all combinations of loss functions and cost equations (Appendix B).

Identifying the true threshold T=5 requires knowledge of the relationship between pest density and average crop loss due to the pest. Since

---

[3]Beta distributions are a family of continuous probability distributions for variables having values between zero and one. This class of distributions can assume a wide variety of shapes including the uniform distribution over (0,1). The shape of an individual beta distribution is determined by the values of the two parameters (Mood, Graybill, and Boes).

conceptually this true relationship represents an effect averaged over all possible occurrences of the pest, it can never be known exactly, but can be estimated from observed occurrences such as experiments. Once this loss function is estimated, the economic threshold can be estimated from it.[4] For example with the linear loss function, an estimate of slope equal to 1.0 instead of the true 1.2 results in an assumed threshold $\hat{T}$ equal to six. If pest densities were known with certainty (i.e., no variability in sample estimates of density), then using an inaccurate threshold would result in higher average cost than using the true threshold. To investigate the effect of inaccurate thresholds that might result from inaccurate estimates of the loss function, a range of assumed thresholds ($\hat{T}$=2.5,4.0, 4.5,5.0,5.5, 6.0,7.5.10.0) were used in the experiment (Figure 1).

2.3.5 Sample Estimates of Pest Density

The decision on whether or not to apply a pesticide was made on the basis of an estimate of pest density. The distribution of pests per plant in the field was specified as a negative binomial distribution with mean equal to the true mean density X, and an index of aggregation equal to 0.5. The index indicates the extent to which pests are clumped or spread out in the field (Harcourt, Southwood). The total sample count was specified to be the sum of the pests counted on N individual, independently chosen plants,

$$\text{count} = \sum_{i=1}^{N} y_i, \text{ where } y_i \sim \text{IID Neg Bin}(\mu=X, \text{ index}=0.5).$$ Because of the

independence of the counts from individual plants, the count for the total sample had a negative binomial distribution with mean equal to the product of sample size N and mean density X, and an index of aggregation equal to the product of N and 0.5: count $\sim$ Neg Bin(NX, .5N). The estimated pest density was specified to be the sample count divided by sample size: $\hat{X}$=count/N. The performance of the threshold rule was assessed for two sample sizes, 30 and 60 plants, to study the effect of differences in the precision of estimated pest density (Figure 1).

III. THE SIMULATION EXPERIMENT

The decision rules for applying pesticides (AR, AN, AT2.5 - AT10.) were

---

[4]The economic threshold can be estimated by using the equality at the threshold density between assumed average crop loss without a pesticide application and assumed average cost with an application.

$$E(L:X=\hat{T},\hat{L}(X)) = E(K:X=\hat{T},\hat{L}(X))$$

$$\hat{L}(\hat{T}) = k' + E(F)\hat{L}(\hat{T})$$

$$\hat{L}(\hat{T}) = k' \,/\, (\,1 - E(F)\,).$$

For the first specification of cost when pesticide was applied, k' was \$6 and F was always 0. For the second specification, k' was \$4.20 and E(F) was .3. Therefore, for both specifications k'/ (1-E(F)) equaled \$6, so regardless of the estimated loss function L, the two specifications result in the same assumed threshold.

compared for each variation of the model (Table 4). For each of the 80 variations, costs for the decision rules were recorded for 400 replications, each of which represented a different combination of actual and estimated pest density, crop loss, and effect of pesticide.[5]

The 400 replications produced a distribution of costs for each of the decision rules. The distribution of costs for AN was the distribution of crop losses for the 400 replications. When pesticide prevented all crop loss, the distribution of costs for AR was 400 observations of cost = $6; when partial crop loss occurred despite pesticide application, the costs varied according to that variable loss. The distribution of costs for the threshold decision rules included some observations equaling cost with pesticide and others equaling cost without pesticide, the cost for each replication being determined by whether or not the estimated pest density called for an application of pesticide.

TABLE 4 Summary of the Simulation Experiment

Component of the Model	Number of Variations
Pest density distributions	5
Crop loss functions	4
Total cost with pesticide	2
Sample sizes for estimating pest density	2

The cost distributions for AR, AN, and AT were compared using three statistics: average cost, standard deviation of cost (SD), and .975 sample quantile of cost (Q975). Average cost was used to estimate average savings from using the threshold rule instead of routine or no pesticide applications. Standard deviation of cost indicated the variability in the performance of a decision rule and was one measure of risk (Anderson, Dillon, and Hardaker; Halter and Dean). The .975 sample quantile was another measure of the risk of high cost. The probability of a cost exceeding this quantile was .025. As an indicator of high costs, the .975 sample quantile was used instead of maximum cost because it has a smaller variance as an estimate of the corresponding population quantile (Mood, Graybill, and Boes, page 257), and was therefore a more stable measure of the position of the upper tail of the cost distribution.

The economic significance of observed differences among decision rules depends on the magnitude of costs and losses. This analysis was scaled around a cost of pesticide application equal to $6 per acre. If the analysis had been scaled around a higher cost, the economic significance of the observed differences would have appeared greater, and the deviations from average cost would have become more important as indicators of risk. Consequently, interpretation of the results should emphasize predominant trends and relationships rather than the magnitude of differences, which depend on the scaling of costs.

---

[5]The procedures used to generate the values of the random variables in model are described in Appendix C.

IV. RESULTS: FACTORS AFFECTING THE VALUE OF THRESHOLD DECISION RULES

4.1 Distribution of Pest Density

The distribution of pest density strongly affected both the number of pesticide applications using the threshold rule AT (Figure 2) and the average savings from using AT instead of routine applications (AR) or no applications (AN) (Figure 3). The gain from AT over AR was highest for the two distributions in which low pest densities predominated (II, IV), while the gain over AN was highest for distributions in which high densities predominated (III, V). The gains from AT over both AR and AN were larger with distribution II than with IV, even though both had probability .75 of pest density being less than the threshold five. Similarly, the gains from AT over AR and AN were larger with distribution V than with III, even though both had probability .25 of pest density being less than the threshold five.

The higher savings with distribution II compared to IV, and with V compared to III resulted from the higher variances of II and V. The higher variance and correspondingly greater occurrence of densities well below and above the threshold increased savings from AT in two ways: 1) the high and low densities were more easily classified as being above or below the threshold than were densities closer to the threshold, and 2) proper classification provided larger savings than for densities near the threshold, where the cost of pesticide and crop loss were more nearly equal. For example, the gain from AT over AN was larger for distribution II than for IV, even though mean and median pest density for distribution II were lower. Distribution II had more low and high densities, while distribution IV had densities concentrated closer to the threshold. The more frequent high densities with distribution II increased the gain from rule AT over AN by increasing the cost of AN, while the low densities in II favored AT by being easy to classify.

Use of AT increased the standard deviation (SD) of cost over AR (Figure 4) but decreased it relative to AN (Figure 5). The differences in the .975 quantile of cost (Q975) exhibited the same trends as differences in SD (Appendix Table D1). The differences in SD and Q975 among rules AT, AR, and AN varied for the five distributions and were closely related to the frequency of pesticide applications because those applications reduced variability from crop loss. The differences between AT and AR in SD and Q975 were larger for the distributions with predominantly low densities and few pesticide applications than for those with high densities and frequent pesticide applications. The differences between AT and AN in SD and Q975 exhibited the opposite trend, being largest for distributions with predominantly high values and frequent pesticide applications.

4.2 Loss Function Relating Pest Density and Expected Crop Loss

The average savings using rule AT were generally larger with the exponential loss function LF4 than with the linear functions LF1, LF2, and LF3 (Figure 3). With the steeper gradient in loss between low and high densities, the savings from avoiding pesticide applications for low densities were higher with the exponential function, while the losses prevented by pesticide for high densities were also larger with the exponential function. The exponential function increased the difference

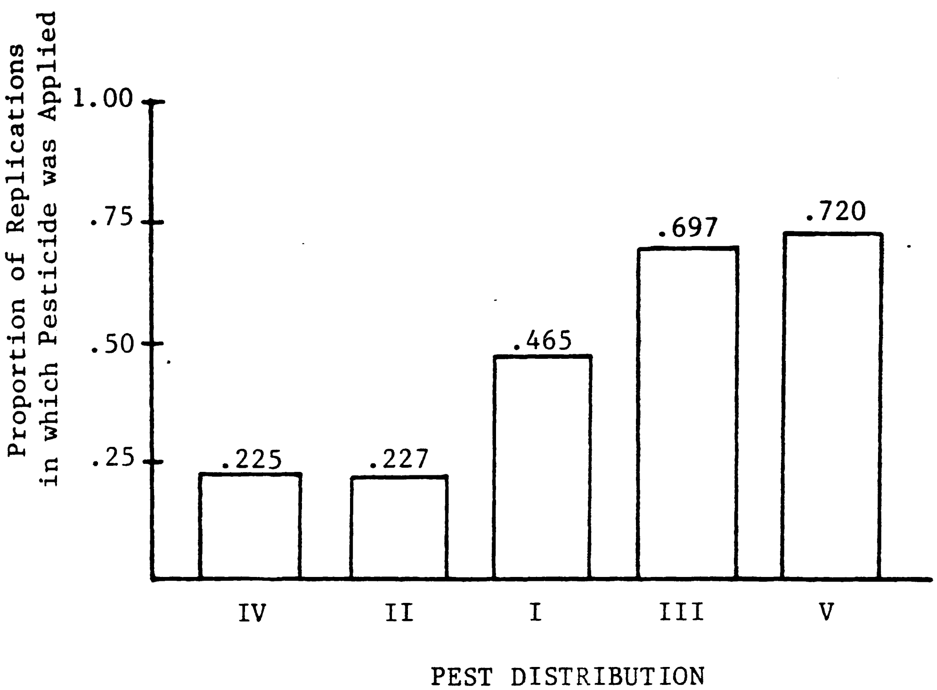


Figure 2. Pesticide Applications Using Threshold ($\hat{T}$=5)

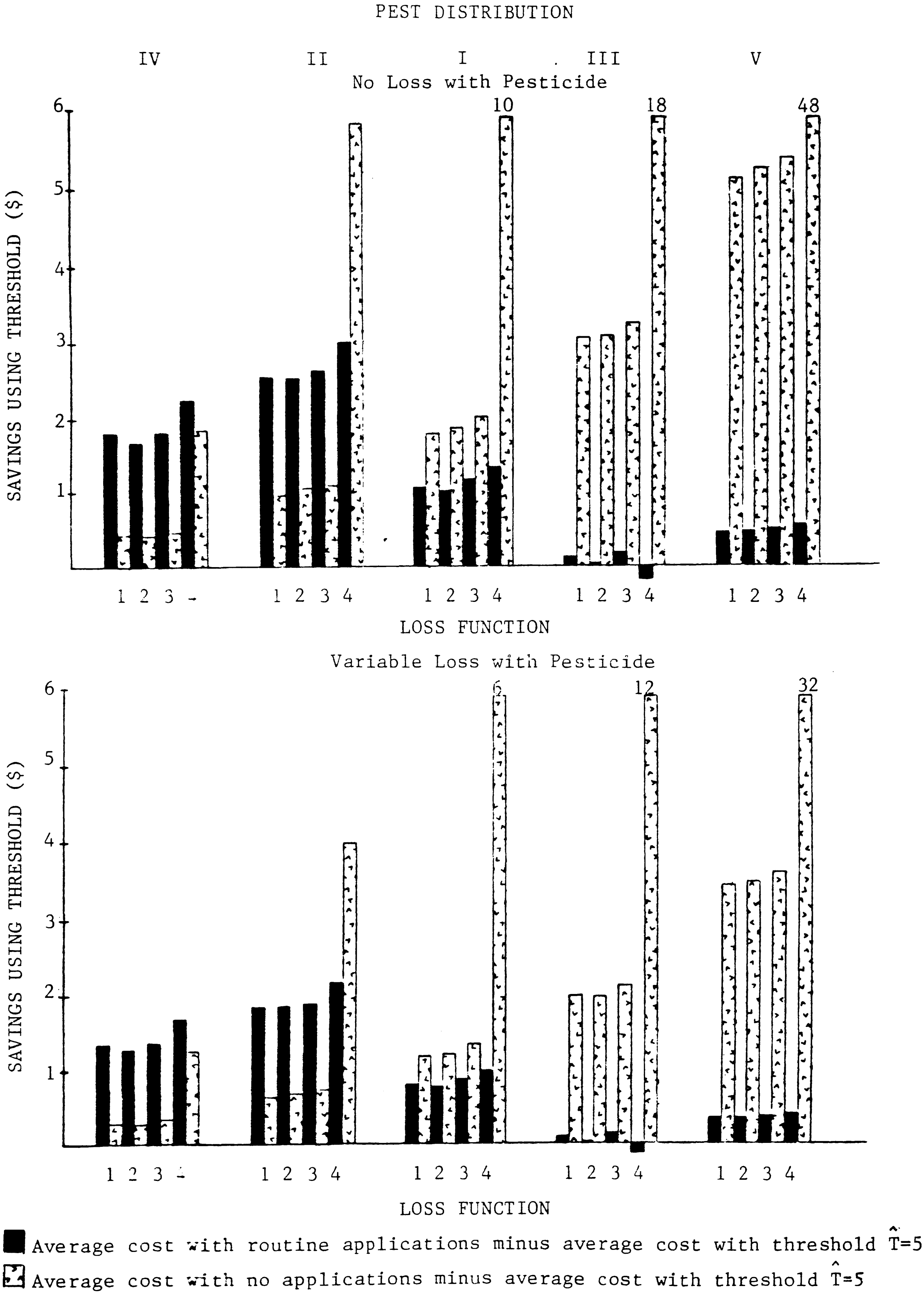


Figure 3. Average Savings from Using Threshold $\hat{T}$=5 when sample size N=30.

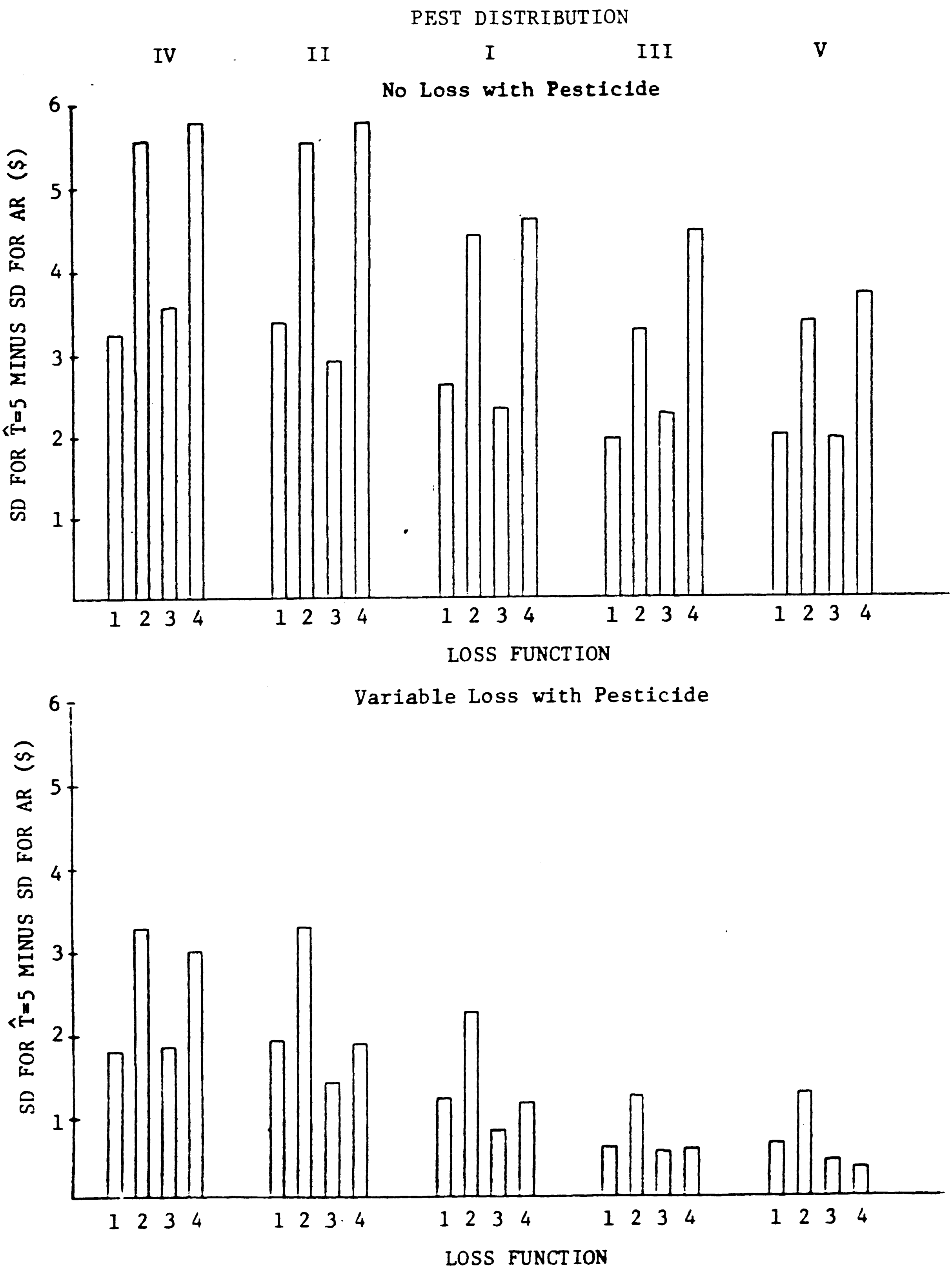


Figure 4. Difference in Standard Deviation (SD) of Cost for Routine Applications (AR) and Threshold $\hat{T}$=5 (AT) when sample size N=30.

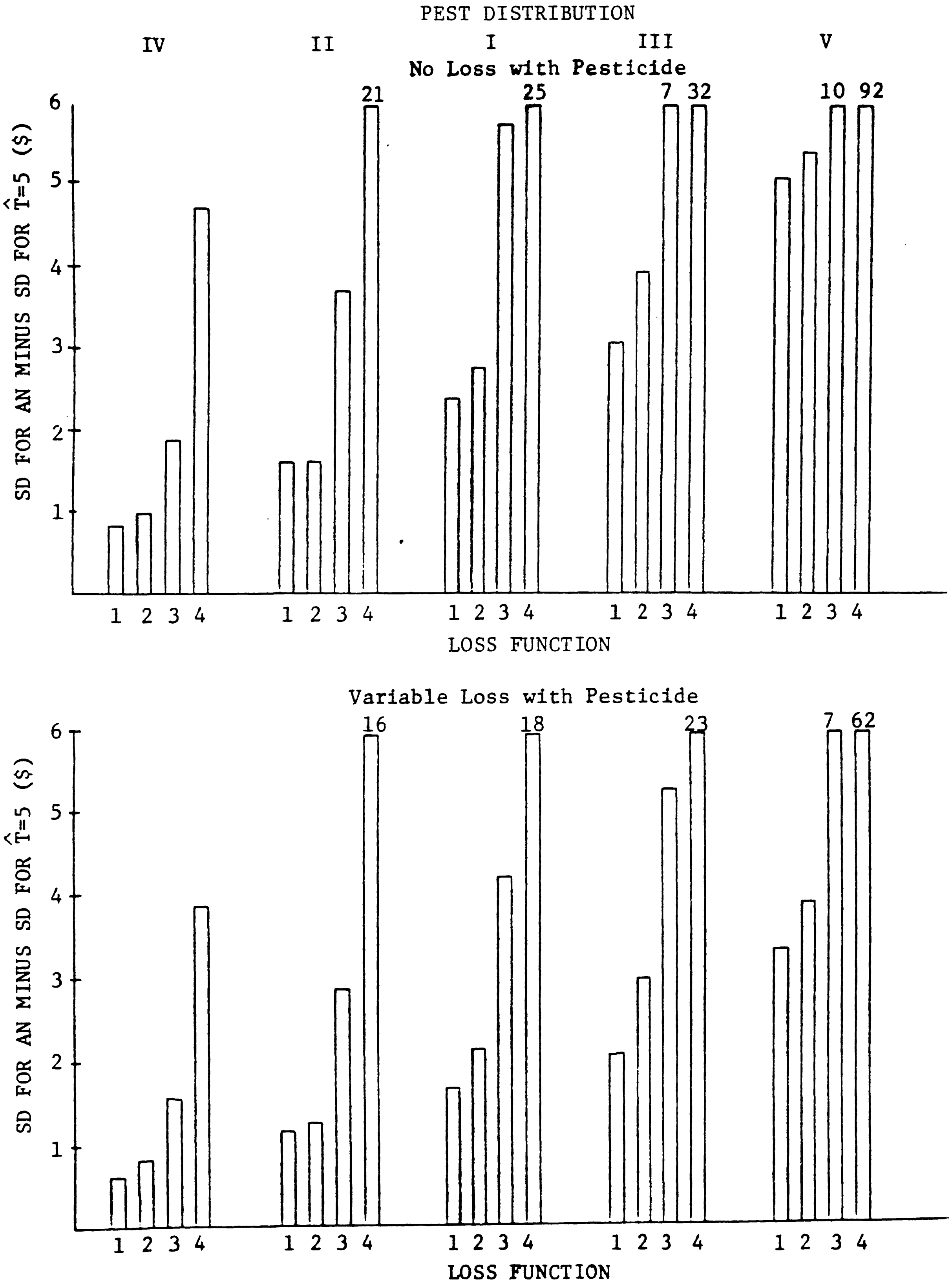


Figure 5. Difference in Standard Deviation (SD) of Cost with No Applications (AN) and Threshold $\hat{T}$=5 (AT) when sample size N=30.

between AT and AN more than it increased the difference between AT and AR because the savings from using AT instead of AR could never exceed $6, while the savings over AN had no limit.

As reflected by the difference in SD between AT and AN, the value of AT for preventing large losses was accentuated by the exponential function (Figure 5 and Appendix Table D1). This accentuated value also was evident in differences in Q975 (Appendix Table D1). The functional form of the average loss component had little effect on the differences in SD and Q975 between AT and AR because AT resulted in sprays for high X values, so differences in crop loss at high X between the linear and exponential functions were not expressed.

4.3 Variability in the Effect of Pest Density on Crop Value

Since the variability component of the loss functions did not affect the expected value of crop loss, average savings from AT for LF1, LF2, and LF3 differed only by small amounts attributable to sampling variability (Figure 3). For each decision, the variability term was as likely to increase the savings from using rule AT instead of AR or AN as it was to decrease savings.

The variability term strongly affected the differences in SD between rules AT and AR (Figure 4). The effect was strong because pesticide applications reduced the fluctuation in crop loss due to variable pest density and thereby increased the relative effect on SD of the variability term. The variability term had a much weaker effect on the differences in SD between AT and AN because the fluctuation in crop loss due to variable pest density had a strong effect on SD for AN, thereby reducing the relative effect of the variability term (Figure 5). The effect of the variability term on differences in Q975 among AT, AR, and AN followed the same pattern as the effect on SD (Appendix Table D1).

The SD and Q975 of AT were lower with the multiplicative variability of LF3 than with the additive variability of LF2. This reduction can be explained by noting that the multiplicative variability was specified to be comparable to the additive variability of LF2 when pest density equaled five. The multiplicative variability varied with pest density; it was lower than the additive variability of LF2 when density was less than five and higher when density was greater than five. Since rule AT called for an application of pesticide in most cases when pest density exceeded five, SD and Q975 for AT were determined primarily by the variability in crop loss for densities less than five. At these densities below five, the multiplicative variability in crop loss was less than the additive variability, so SD and Q975 for AT also were less.

By lowering the SD and Q975 of rule AT, the multiplicative variability improved the performance of AT relative to rules AR and AN. The multiplicative variability further improved the performance of AT compared to AN by increasing the SD and Q975 of AN.

4.4 Effectiveness of Pesticide

Number of pesticide applications and standard deviation of cost had a strong negative correlation when applications were specified to have a constant total cost of $6. This specification removed all variability when pesticide was applied, so decision rules that resulted in many applications had low variability in cost. The alternative specification of total cost with pesticide applications included partial crop loss, so cost with pesticide was related to the loss that would have occurred without pesticide. This specification reduced the differences in SD among the three decision rules, thereby improving the performance of AT compared to AR but reducing its advantage compared to AN (Figures 4 and 5). The alternative specification had a similar effect on differences in Q975 among the three decision rules AR, AT, and AN (Appendix Table D1).

The change to the second specification of cost with pesticide also reduced the average savings from the threshold rule over rules AR and AN (Figure 3). AT saved less by avoiding applications for low pest densities because the cost of application was $4.20 instead of $6, and reduced losses by less when applications were made for high densities because partial losses occurred despite the application.

The observed reduction in savings using AT instead of AR, however, is not a true indication of the effect that partial crop loss would have on AT compared to AR. The cost of purchasing and applying pesticide was changed from $6 to $4.20 so that the threshold remained five. Retaining the same threshold facilitated study of the effect of partial crop loss on SD of cost for rules AT and AR, but was inappropriate for comparing savings with and without partial crop loss.[6] If the cost of pesticide application had not been changed from $6 to $4.20, the savings using AT instead of AR would have been higher when pesticide cost included partial crop loss than when cost was $6 without any crop loss. Also, if the cost of purchasing and applying pesticide had remained $6 instead of being changed to $4.20, the true threshold for the linear loss functions would have been:

$$1.2\,T = 6 + .3(1.2T)$$
$$T = 7.1$$

As a result of the higher threshold, application of pesticide would have been inappropriate for a larger proportion of pest densities. The increased savings from not applying pesticide for low pest densities and the larger proportion of densities below the threshold would both favor AT versus AR. Conversely, if the cost with pesticide application had been $6 plus partial crop loss, the savings from using AT instead of AN would have been less than those observed when cost was $4.20 plus partial loss.

4.5 Accuracy of Information Available to Decision Maker

4.5.1 Threshold Used to Determine Whether to Apply Pesticide

---

[6]By retaining the same threshold, comparison of results for the two specifications of cost was not confounded by changes in frequency of pesticide application or in the position of the threshold compared to distribution of losses without pesticide. Without these confounding effects, the results more clearly illustrate the effect of partial crop loss with pesticide on the difference in SD between rules AT and AR.

The threshold between 2.5 and 10.0 used to determine whether to apply pesticide affected cost and the number of pesticide applications for the 400 replications. Differences among the thresholds reflect the cost of inaccurate estimation of the threshold, and the potential for changing short- and long-run costs by changing the threshold used for decisionmaking. The observed differences among thresholds in number of pesticide applications, average cost, and standard deviation of cost were strongly influenced by the distribution of pest density and the loss function relating pest density and crop loss (Figures 6a-6e).[7]

The performances of thresholds AT4 through AT6 were generally comparable to the performance of the true threshold (AT5). Both average cost and standard deviation of cost differed little within this range. The frequency of pesticide application was moderately different for AT4 and AT6. This difference was largest with pest distributions I, III, and IV for which the absolute difference in frequency of application between AT4 and AT6 was approximately .25 (Figures 6a-6e and Appendix Table D2). The absolute difference with both distribution II and V was .15. The difference between AT4 and AT6 was smaller for distribution II because densities were predominantly below four so AT4 often resulted in the same decision about pesticides as did the higher thresholds. The difference was small for distribution V because of the many densities above six. The difference in frequency of applications between AT2.5 and AT10 was large with all pest distributions, ranging from an absolute difference of .47 with distribution II to .75 with distribution III.

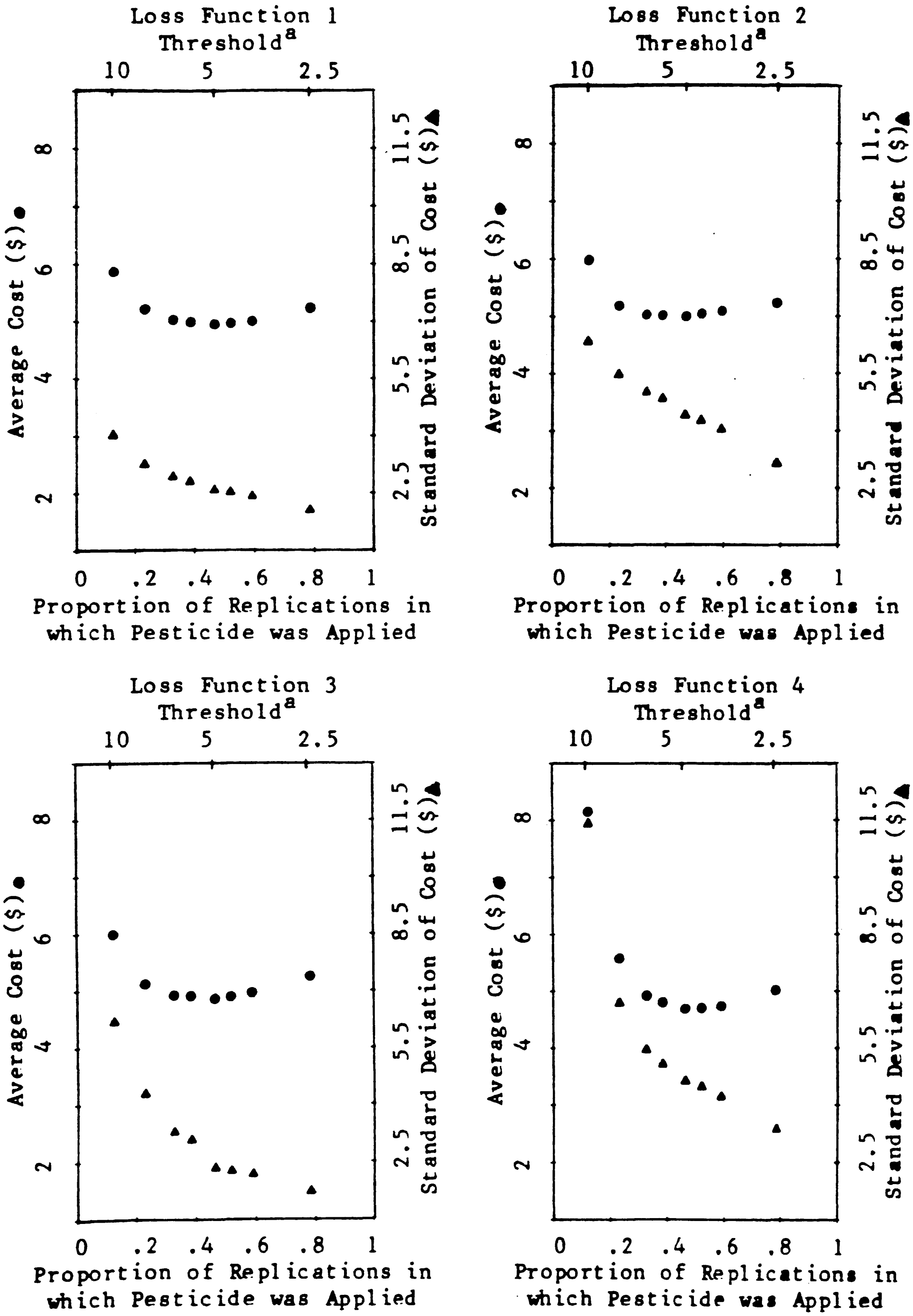
The difference in average cost between AT2.5 and AT10 varied among pest distributions and loss functions. For pest distributions I, II, and IV average cost generally differed little among thresholds, an exception being with the exponential loss function (LF4) for which cost increased at the high thresholds. For pest distributions having many high values (III and V), cost increased significantly at high thresholds, especially with LF4. With distribution III and LF4, AT4.5 produced lower costs than the true threshold AT5, presumably because of the higher probability of correctly calling for pesticide application for densities above five.

When savings from AT5 compared to routine (AR) or no applications (AN) were small, inaccurate thresholds often reduced savings by a large proportion, although the absolute difference in cost between the true and estimated thresholds was small. The cost of an inaccurate threshold was highest for the high pest distributions (III and V) and exponential loss function (LF4).

---

[7]Figures 6a-6e do not show results for AR(=AT0.0) or AN(=AT∞) because the results for AR were constant and those for AN exceeded the maxima on the axes for several pest densities and loss functions. By definition, the proportion of replications with pesticide application was 1.0 for AR and 0.0 for AN. Figures 6a-6e report the results from when pesticide prevented all crop loss to the pest, so average cost for AR was $6 and standard deviation of cost was $0. The values of average cost and standard deviation of cost for AN can be obtained using the comparison between AN and AT5 in Figures 3 and 5.

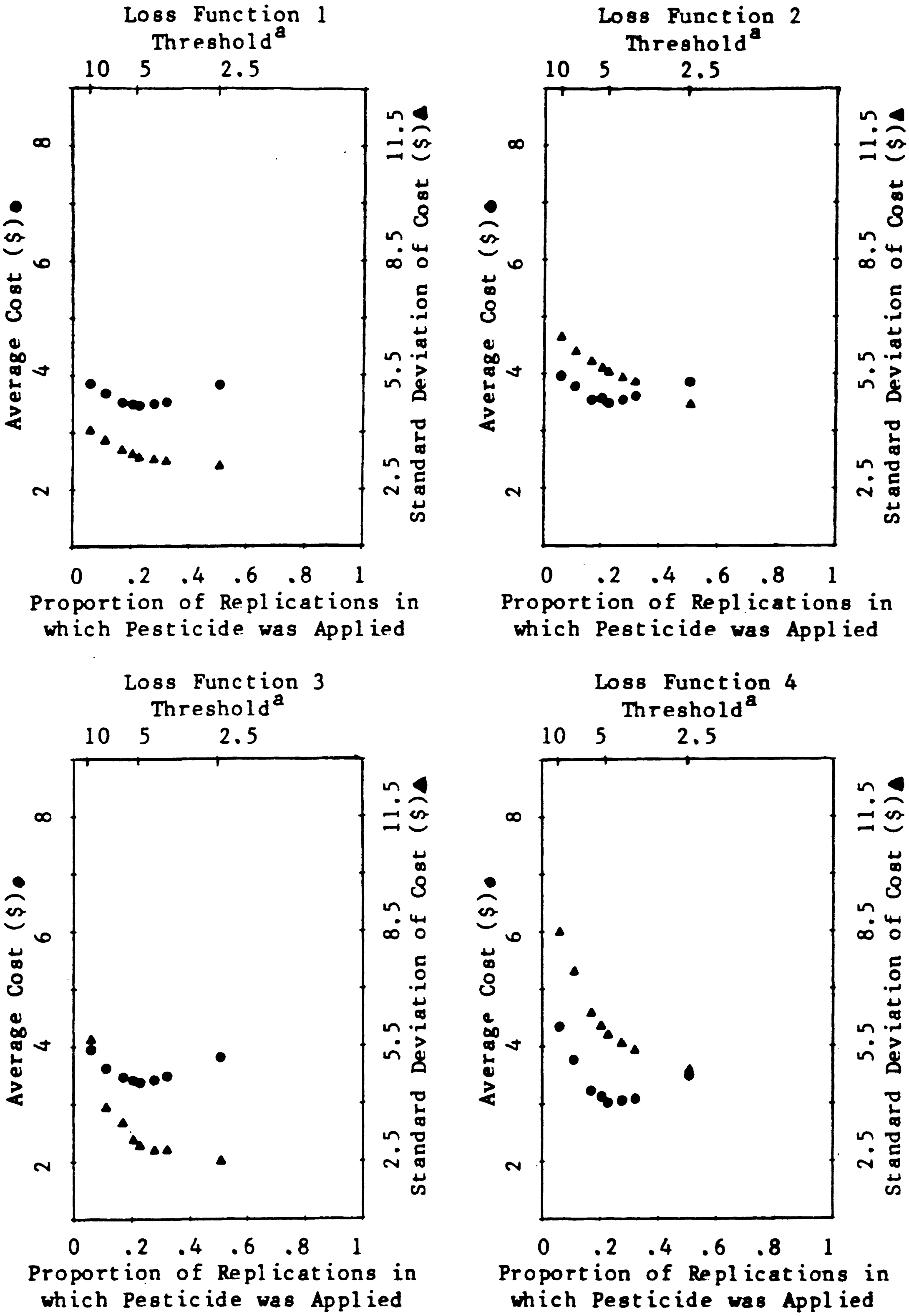
PEST DISTRIBUTION I



[a] Threshold values are plotted according to the associated proportions of pesticide applications.

Figure 6a. Effect of different thresholds on cost and pesticide use for Pest Distribution I when pesticide prevents all crop loss and sample size N=30.

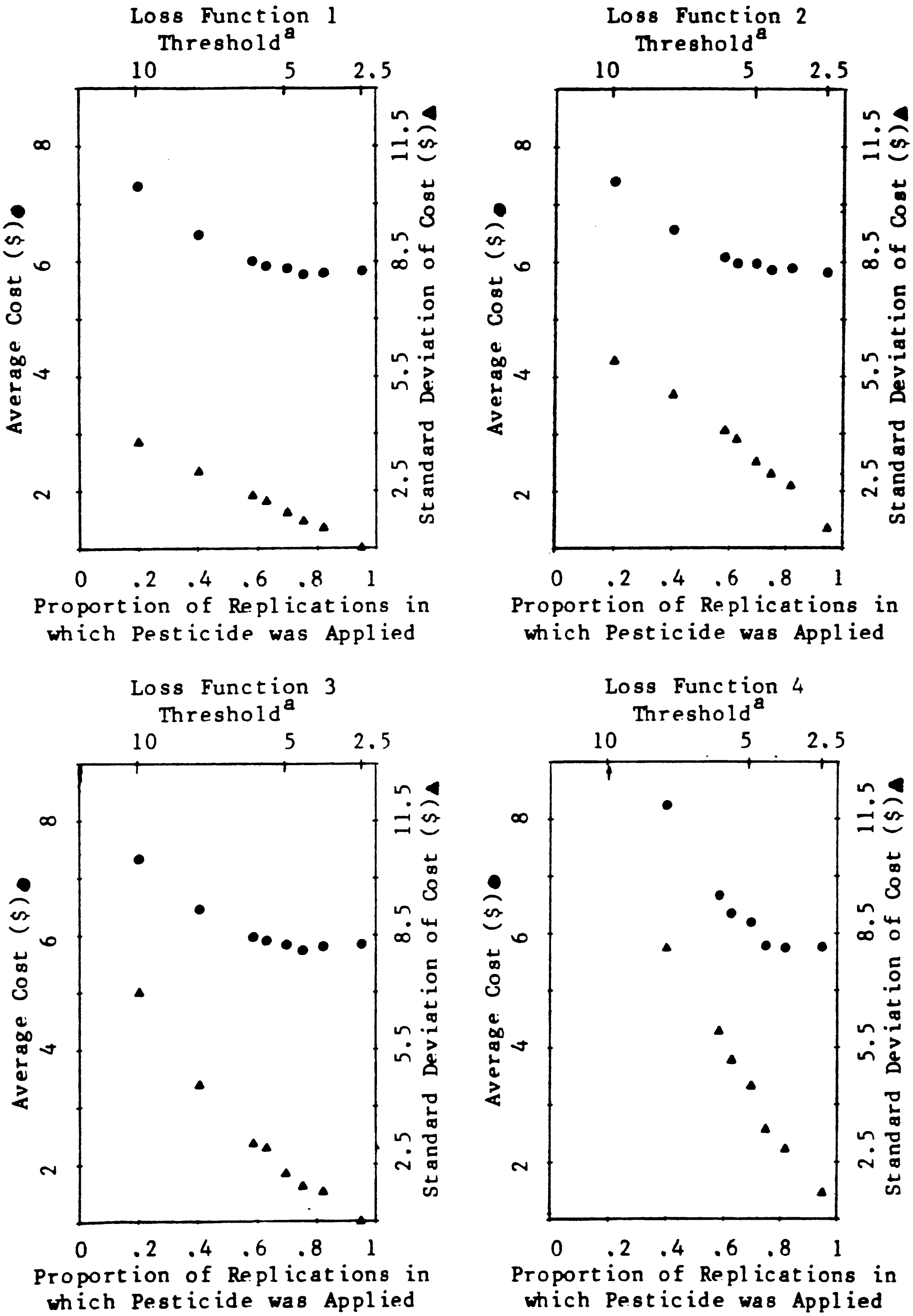
PEST DISTRIBUTION II



[a] Threshold values are plotted according to the associated proportions of pesticide applications.

Figure 6b. Effect of different thresholds on cost and pesticide use for Pest Distribution II when pesticide prevents all crop loss and sample size N=30.

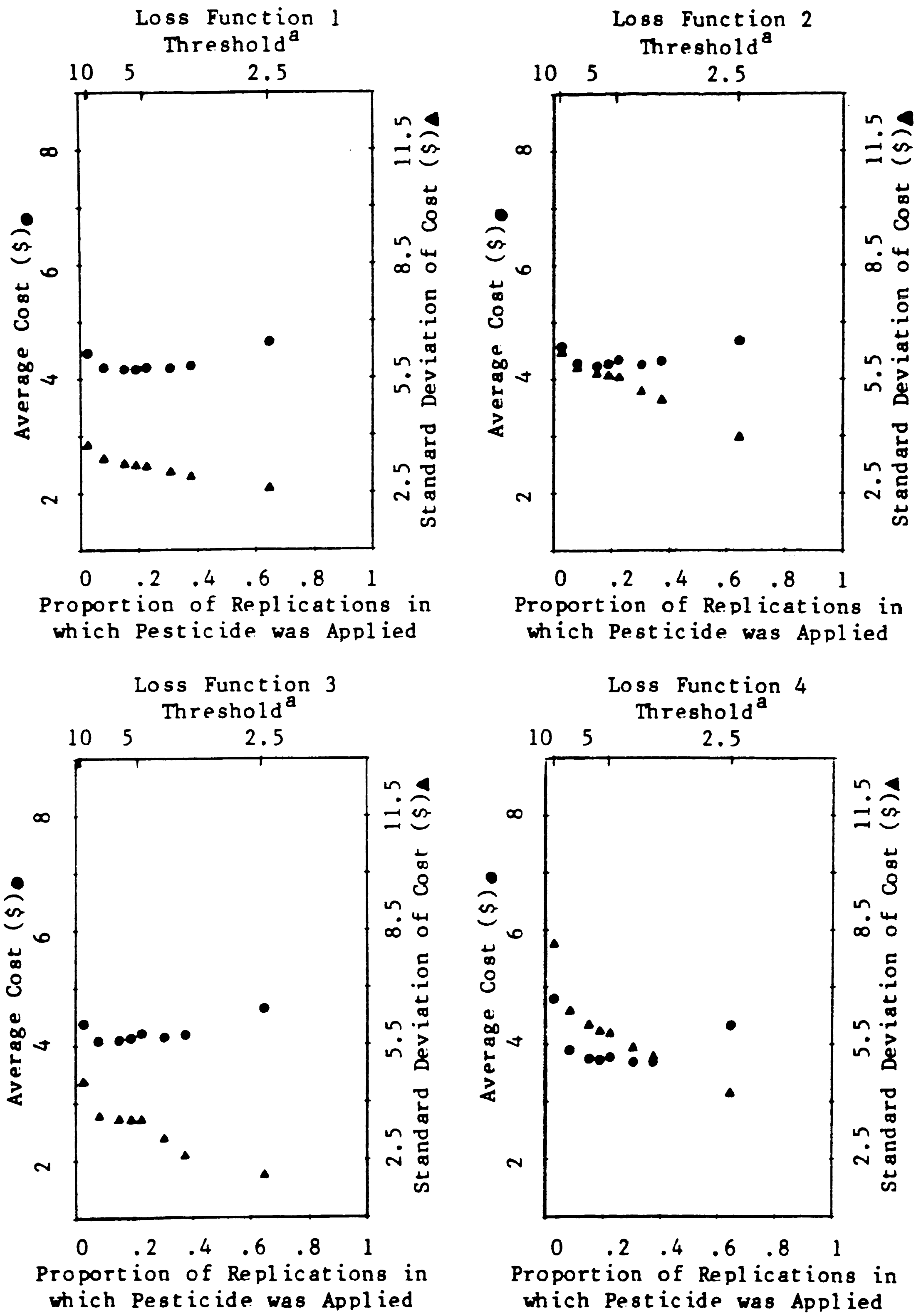
PEST DISTRIBUTION III



[a] Threshold values are plotted according to the associated proportions of pesticide applications.

Figure 6c. Effect of different thresholds on cost and pesticide use for Pest Distribution III when pesticide prevents all crop loss and sample size N=30.

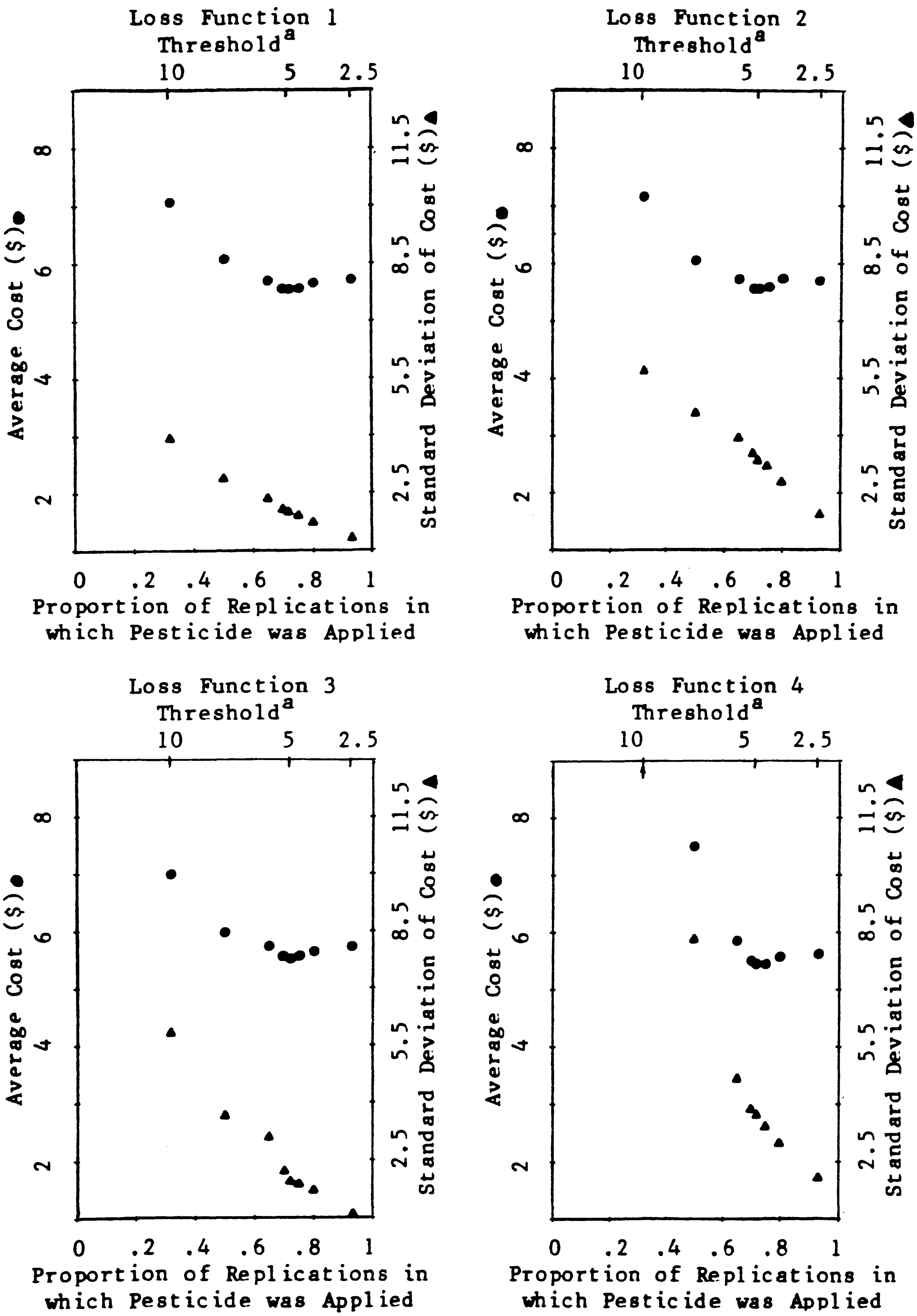
PEST DISTRIBUTION IV



[a] Threshold values are plotted according to the associated proportions of pesticide applications.

Figure 6d. Effect of different thresholds on cost and pesticide use for Pest Distribution IV when pesticide prevents all crop loss and sample size N=30.

PEST DISTRIBUTION V



[a] Threshold values are plotted according to the associated proportions of pesticide applications.

Figure 6e. Effect of different thresholds on cost and pesticide use for Pest Distribution V when pesticide prevents all crop loss and sample size N=30.

Differences among thresholds in standard deviation (SD) and .975 quantile (Q975) of cost were determined primarily by differences in the number of pesticide applications. SD increased as thresholds increased and number of applications decreased (Figures 6a-6e and Appendix D Tables); Q975 exhibited the same trend as SD (Appendix D Tables). The increase in SD and Q975 at higher thresholds was steepest with the exponential (LF4) and multiplicative (LF3) loss functions and the high pest distributions (III and V). When the cost with pesticide applications included partial crop loss, the differences among thresholds diminished because the costs with and without pesticide were related (Appendix D Tables).

4.5.2 Sample Size and Precision of Estimated Pest Density

Increasing the precision of estimated pest density by increasing sample size from 30 to 60 had little effect on the performance of the true and assumed thresholds (Appendix D Tables). When the two sample sizes resulted in different decisions about applying pesticide, the pest density was usually near the threshold so the difference between the costs with and without pesticide was small. The largest benefits from increasing sample size occurred when pest densities were clustered just above the threshold and losses increased rapidly at densities exceeding the threshold (i.e. with LF4).

V. LIMITATIONS OF THE MODEL USED IN THE EXPERIMENT

The following characteristics of the model limit its applicability:

1. the interdependencies among current and subsequent pest management decisions are not represented,

2. the cost of information about the threshold and pest density is not included explicitly,

3. the effectiveness of pesticide applied routinely is assumed to be equal to the effectiveness of pesticide applied according to the threshold rule, and

4. only one variability term was included in the loss function to represent the combined effect of many sources of variability that may differ greatly in their relationship with pest density.

Since the pest distributions and loss functions in the experimental model did not change as a result of previous decisions, the effect of these decisions on subsequent pest problems was not taken into account formally in the experiment. The model is static and appropriate only for comparing performances of alternative decision rules for single decisions or sequences of independent decisions for which pest distributions and loss functions remain unchanged. The 400 replications for each model specification are intended to increase the precision of the estimated performance of the decision rules for a single decision, and do not remedy the weaknesses of the experiment for assessing the changes in pest problems or knowledge about them that may occur as a result of previous decisions.

One consequence of the static model is that it provides no insights into how pest problems and costs may change over time in response to the use of pesticides. Presumably, as a result of resistance and disruption of naturally occurring biological controls, pest problems and costs may increase over time in response to the use of pesticides, so an objective of a pest management program may be to reduce the number of pesticide applications. Although the model cannot be used to estimate the effect on future costs from reducing the use of pesticides, it does indicate the effect on current cost from not applying pesticide, and identifies situations for which current cost and pesticide applications both may be reduced.

Another consequence of the static model is that it does not account for new information about the crop and pests that may be acquired over time. If this learning, such as about pest distributions and losses, is affected by management decisions, then current decisions may affect the capability for improving future decisions. Although the effect of decisions on learning is not represented in the model, the model does illustrate the effect of learning to reduce the variance of the loss function's variability component and to improve the accuracy of the threshold.

Another limitation of the model is the omission of the cost of acquiring information about thresholds and pest density. The results of the experiment reflect only the potential benefits of the threshold rule from reducing costs of pesticide and crop loss. Equally important factors for determining whether to develop a threshold decision rule are the cost of research for estimating the threshold, and the cost of sampling for estimating pest density.

In this experiment, pesticide applied routinely and pesticide applied according to threshold rules were assumed to be equally effective. This assumption may be inappropriate for some pest problems. Sampling pest populations to decide whether to apply pesticide may also indicate the date it should be applied. As a result, pesticide applied according to a threshold and sampling may prevent crop loss more effectively than pesticide applied routinely without sampling. Conversely, routine application may be more effective if sampling interferes with timely application, or precludes the use of the most effective pesticide. A systemic pesticide applied routinely during planting, for example, may be more effective than a foliar application of another pesticide after sampling. Differences in effectiveness between routine and threshold applications could be represented in the model by specifying a different cost equation for each.

Another restriction in the model that could be relaxed by minor modification is the single term in the variability component of the loss function. This term represents the combined effects of factors such as price of the crop and interaction among pests. These factors may differ strongly in the way the variability associated with them is related to pest density. The additive and multiplicative specifications of the variability component represent two extremes in this relationship between variability and pest density, but neither may fully portray the combined effects of all factors. The model therefore might be improved by including two terms in the variability component of the loss function, perhaps one multiplicative and the other additive.

VI. CONCLUSIONS

6.1 Conclusions about Factors Affecting the Value of Threshold Decision Rules

Average savings and frequency of pesticide applications using rule AT were both determined primarily by the distribution of pest density among fields and growing seasons. The distribution therefore is the principal determinant of the usefulness of the threshold rule for reducing short-run costs and possible external and long-run costs of pesticides. The position of the distribution relative to the threshold had the strongest effect on performance of AT, but the variance of the distribution also was important. Even if crop loss is highly dependent on pest density, estimates of this density are not needed for effective management unless density and resulting crop loss are variable.

A steeply increasing loss function such as an exponential function increases the range of crop losses and, more specifically, increases the difference in crop loss between densities below and above the threshold. The larger difference in loss for densities below and above the threshold increases the potential for savings using AT, but also increases the cost of inappropriate decisions due to inaccurate estimates of pest density or the threshold.

While variability in pest density and crop loss favor rule AT, variability in losses for particular densities detracts from AT by reducing the predictive value of estimated pest density for deciding whether an application of pesticide is appropriate. Consequently, one measure of the suitability of AT is the proportion of total variability in crop loss to the pest that is accounted for by variability in pest density. As this proportion increases relative to the proportion that varies independently of pest density, the potential for using the threshold rule increases. For evaluating the potential of a threshold rule, the variability in crop loss at pest densities below the threshold is more important than the variability at densities above the threshold because the threshold rule would usually result in application of pesticide at densities above the threshold.

Another useful measure of the potential value of rule AT is the combined cost of pesticide and crop loss to the pest compared to the total value of the crop. As the relative cost of pesticide and crop loss increases, the potential savings from using AT increase, but so do the risks from using it.

6.2 Conclusions about Quality of Information and the Value of Threshold Decision Rules

The performance of rule AT may be moderately insensitive to inaccurate estimates of the threshold. Average savings in this experiment, for example, were fairly constant for estimated thresholds in the range $\hat{T}=4$ through $\hat{T}=6$. For the linear loss functions, this range of thresholds corresponds to estimates of average crop loss per pest per plant of \$1.50 to \$1.00 compared to the true cost specified to be \$1.20. Consequently, estimates of average crop loss in experiments could depart from the true average by approximately 20 percent and the corresponding estimate of the threshold might still provide close to optimal savings. The experimental conditions, however, must be representative of the commercial conditions in which the threshold will be used, and estimating average loss within 20 percent of the true average for commercial conditions may be difficult and costly. Comparison of this cost with the potential savings from AT is an important consideration for deciding whether to adopt the threshold approach.

The comparability of average savings for a range of thresholds offers the potential for choosing thresholds to attain other objectives, such as minimizing the frequency of pesticide applications or the incidence of large crop loss, while obtaining average savings comparable to those from the threshold that maximizes average savings.

Increasing the precision of estimated pest density may reduce the frequency of inappropriate decisions about applying pesticide, but may have little effect on average savings or incidence of large losses because the pest densities most likely to be misclassified by imprecise estimates are those near the threshold for which costs with and without pesticide are nearly equal. Consequently, error rates (Fohner 1981, Onsager) indicating the probability of misclassifying pest densities relative to the threshold density are inadequate for evaluating sampling procedures. Instead, sampling should be evaluated according to the cost of wrong decisions resulting from imprecise estimates.

The evaluation in this study of the effect of sample size did not reflect the full effect of sampling procedures. In this experiment the distribution of pests among plants in the field was specified to be perfectly represented by a negative binomial distribution. In farmers' fields, the spatial distribution of pests will depart from assumed distributions, and density may differ greatly among parts of the sampled area. Also, in this study, the number of pests on the sampled plants were assumed to be counted exactly without measurement error, while in reality measurement errors may be common. Although the benefits from increasing the precision of estimates may be small when spatial distributions are known and counts are errorless, the benefits of improved sampling procedures may be large when spatial distributions are unknown and vary among fields, and counts include errors.

In addition to estimates of pest density, sampling may provide important information about age structure, dispersion, and other attributes of pest populations. By monitoring these attributes and using the information to predict losses, decisions about pesticide application may be improved. In terms of the model of decisionmaking in this study, utilizing attributes in addition to pest density can be viewed as incorporating one or more additional terms in the loss function, and thereby accounting for some effects formerly included in the variability term. Reducing this variability by monitoring attributes of the pest population may be important for reducing the risk associated with threshold rules.

A complete evaluation of sampling procedures and the threshold decision rule requires information about the cost of sampling. For example, the results of this study suggest that samples of less than 30 plants might have performed adequately. For many pests, however, the principal cost of sampling is for transportion to the field and time spent traversing it (Fohner 1982). Cost may depend only minimally on the number of plants inspected during the traverse of the field, so reducing sample size may have little effect on cost of using the threshold.

6.3 Classifying Pest Problems According to Their Suitability for Threshold Decision Rules

This experiment indicates characteristics of pest problems that are conducive to threshold decision rules and others that are not. Among the pest problems that are conducive to the threshold rule are those in which pest densities on both sides of the threshold are common and are often well above or below it. The occurrence of densities on both sides of the threshold favors the threshold rule compared to either fixed rule. The densities that are far from the threshold are easiest to classify and provide the largest savings for correct decisions. Pest densities that are consistently above or consistently below the threshold are not conducive to the threshold approach. If management using the threshold rule is almost always the same as a fixed decision rule, e.g. AR or AN, then estimates of pest density will have little value, and, when sampling costs are considered, the threshold rule may cost more than the fixed rule.

The threshold rule may be useful for some pest problems even though pest densities are consistently below the threshold. If average cost is minimized by never applying pesticides but most farmers apply them routinely, then the threshold rule may serve as a transitional rule while the advantages of not applying pesticide are demonstrated. Also, if pest densities are generally low but occasionally high and costly, the threshold rule may have higher average cost than never applying pesticide, but may be favored because it prevents occasional large losses.

Threshold rules may be undesirable if variability in the effect of pest density on crop value is high and pest-related costs are a significant part of production costs. Estimates of pest density may reduce uncertainty about subsequent crop loss but will not eliminate it. If the range of possible crop losses remains wide despite knowledge of pest density, then decisions based on density are risky, especially if pest-related costs are large. In these situations, decision rules might be improved by using other variables instead of, or in addition to, pest density to predict crop loss.

The potential of a threshold rule is enhanced if measurement of pest density provides timely, relatively precise predictions of crop loss. If crop loss can be predicted accurately on the basis of estimated pest density then decisions and prompt action based on those estimates will involve little risk. Precise estimates of pest density are especially valuable when the average crop losses from pest densities on either side of the threshold differ substantially. With this substantial difference in cost, pesticide applications for high densities will prevent large losses, while avoiding applications for low densities will also bring large savings.

A rapid increase in average crop loss at pest densities above the threshold, however, may be a disadvantage for the threshold rule if densities are often slightly greater than the threshold. Pest densities near the threshold are the most likely to lead to inappropriate decisions due to sampling variability or measurement error. If these densities are frequent, inappropriate decisions will be also. The cost of these inappropriate decisions may be high if loss increases rapidly above the threshold.

The potential value of the threshold rule is high if the costs of pesticide and losses to the pest are both high compared to the cost of sampling to estimate pest density. Although high pest-related costs result in high costs for inappropriate decisions, they also offer potentially large savings that allow flexibility in the use of the threshold rule. For example, high potential savings may support more costly sampling of pest density and other relevant variables to reduce the probability of costly inappropriate decisions. The risk of large crop loss could also be reduced by lowering the decision threshold. If potential savings are high, then the reduced average savings using the low threshold may still exceed the cost of sampling while reducing the risk of mistakenly not applying pesticide.

A threshold rule is unlikely to be justified in terms of short-run costs if the cost of sampling to decide whether to apply pesticide is comparable to the cost of pesticide. A threshold rule also may be unsuitable if pesticide is inexpensive compared to the value of the crop and the potential effect of the pest. If the cost of pesticide is low compared to crop value, then pesticide is warranted for preventing small crop losses, and accurately estimating the threshold is likely to be difficult. For example, with a pesticide cost of $10 per acre and average crop value of $1,000 per acre, estimating the threshold requires identifying the pest density resulting in an average loss in marketable yield of one percent. Detecting such low levels of loss in experiments would be difficult. Under these circumstances in which pesticide is relatively inexpensive and thresholds may be inaccurate, the threshold rule would be hard to justify in terms of short-run costs when compared to routine pesticide applications, especially if poor decisions may result in large losses.

If the pesticide is suspected to have a negative effect on human health, the environment, or future productivity of agriculture, then the threshold rule may be favored even if the crop loss function and true threshold are difficult to estimate. In this situation, a threshold rule might be chosen to reduce pesticide applications and to prevent large detectable losses, while the question of optimal short-run decisions remained unresolved because of the difficulties of estimating the loss function.

If the long-run and external costs of the pesticide are high, the threshold rule may be desirable even if it increases short-run costs. For many distributions of pest density, thresholds can be chosen that greatly reduce pesticide applications while still preventing large losses and not significantly increasing average short-run cost. For these distributions, a threshold decision rule can reduce the external and long-run costs from pesticides while minimizing the risks and short-run costs that discourage farmers from reducing their use of pesticides.

Summary of Situations For Which the Threshold Decision Rule is Suitable

1. Measurement of pest density provides timely, accurate predictions of crop loss, and management options are available for responding effectively to those predictions.

2a. Pest densities on both sides of the threshold are common and are often well above or below the threshold; or

b. pest densities are consistently below the threshold, but most farmers apply pesticides regularly, or high and costly densities sometimes occur;

3a. the cost of pesticide and losses to the pest are both high relative to the cost of estimating pest density; or

b. the external and long-run costs of pesticides are high.

6.4 Steps for Evaluating Potential Performance of Decision Rules

The economic impact of a pest depends on many variables in addition to pest density such as weather and crop condition (Smith; Stern 1975; Hull and Dunning), so decisionmaking may be guided by information about these other variables in addition to or instead of information about pest density. Consequently, economic thresholds based on pest density can be regarded as only one of a broad group of decision rules for using information about the crop ecosystem to adjust pest management. Identifying the most promising rules and variables is imperative because of the high cost of developing and implementing new management practices (Good; Stern 1973; Way; Way and Cammell). Even when the cost of monitoring a variable and using a decision rule appears low compared to potential savings, the opportunity cost may be high in terms of time spent by researchers and extension professionals.

To evaluate the potential performance of decision rules based on pest density or other variables the following steps should be taken:

1. The costs and effectiveness of current management practices should be assessed.

2. Measurable variables that are correlated with subsequent crop loss should be identified.

3. The distribution of the measured pest variable should be described, even if only in terms of the range of most probable values and possible extremes.

4. At least an approximate quantitative relationship between the measured variable and crop loss should be described.

5. The precision with which crop loss can be predicted from the measured variable should be assessed, including assessment of the effect of variability in price of the crop on those predictions.

Decision rules should be based on variables that are easily measured and highly correlated with crop loss. If research on sampling methods, the occurrence of the pest, and its effect on the crop are performed together, then the variables and results associated with each of these efforts are more likely to be compatible and to lead to effective decision rules.

6.5 Uses of This Analysis

The concepts, methods, and results of this analysis of economic thresholds may contribute in three ways to pest management programs. First, the analysis may contribute at a conceptual level as a framework for evaluating decision rules and sampling procedures. By illustrating the interdependencies among decision rules, sampling procedures, quality of information, and characteristics of the pest and crop, the framework may coordinate and improve the acquisition and use of information about pests and their effects on crops.

The results of this analysis may contribute to pest management programs in a second way by classifying situations according to suitability for threshold decision rules, and assessing the importance of various factors in determining that suitability. This classification and assessment are a starting point for evaluating the potential of threshold decision rules for particular situations.

If enough is known about the crop and pest, the simulation methods used in the analysis can contribute to pest management programs in a third way as a means of estimating the value of information about pest density and its effect on the crop. These estimates can be used to select sampling procedures and decision rules, and to set research priorities.

REFERENCES

Anderson, J.R., J.L. Dillon, and J.B. Hardaker. Agricultural Decision Analysis. Ames: Iowa State University Press, 1977.

Apple, J.L., P.S. Benepal, R. Berger, G.W. Bird, A.P. Gutierrez, F. Maxwell, W.G. Ruesink, P. Santelmann, and G.B. White. Integrated Pest Management. Intersociety Consortium for Plant Protection, 1979.

Boethel, D.J. and R.D. Eikenbary (eds.) Pest Management Programs for Deciduous Tree Fruit and Nuts. New York: Plenum Press, 1979.

California Agriculture. Special Issue: Integrated Pest Management. 32(February 1978).

Flint, M.L. and R. van den Bosch. Introduction to Integrated Pest Management. New York: Plenum Press, 1981.

Fohner, G. Sequential Sampling for Pest Management. Staff Paper 81-12, Dept. of Agricultural Economics, Cornell Univ., Ithaca, New York 14853-0398, 1981.

Fohner, G.R. The value of information for pest management for potatoes. Ph.D. Thesis, Department of Agricultural Economics, Cornell University, Ithaca, NY 14853-0398, 1982.

Glass, E.H. (coordinator) Integrated Pest Management: Rationale, Potential, Needs, and Improvements. Special Publication 75-2, Entomological Society of America, 1975.

Good, J.M. Integrated pest management -- A look to the future. ESC 583, Extension Service, USDA, 1977.

Halter, A.N. and G.W. Dean. Decisions Under Uncertainty. Cincinnati: South-Western Pub. Co., 1971.

Hammersley, J.M. and D.C. Handscomb. Monte Carlo Methods. New York: John Wiley and Sons Inc., 1964.

Harcourt, D.G. "Population dynamics of Leptinotarsa decemlineata (Say) in eastern Ontario: I. Spatial pattern and transformation of field counts". Canadian Entomologist. 95(1963):813-820.

Havlicek, J. and J.A. Seagraves. "The 'cost of the wrong decision' as a guide in production research." Journal of Farm Economics. 44(1962):157-168.

Headley, J.C. "Defining the economic threshold." in the National Academy of Sciences. Pest Control Strategies for the Future. p. 100-108.

Huffaker, C.B. (ed.) New Technology of Pest Control. New York: John Wiley and Sons, 1980.

Hull, R. and R.A. Dunning. "Problems of estimating the need for and timing of control measures against pests and diseases of crops." EPPO Bulletin. 10(1980):3-9.

IMSL Reference Library. Houston: IMSL, Inc., 1980.

Mood, A.M., F.A. Graybill, and D.C. Boes. Introduction to the Theory of Statistics. 3rd ed. New York: McGraw-Hill Inc., 1974.

Naylor, T.H. (ed.) Computer Simulation Experiments with Models of Economic Systems. New York: John Wiley and Sons, 1971.

Onsager, J.A. The Rationale of Sequential Sampling, with Emphasis on its Use in Pest Management. Technical Bulletin 1526, USDA, 1976.

Shannon, R.E. Systems Simulation: the Art and Science. New Jersey: Prentice-Hall, Inc., 1975.

Smith, R.F. "Principles of measurement of crop losses caused by insects." FAO Symposium on Crop Losses. 1967.

Southwood, T.R.E. Ecological Methods. London: Chapman and Hall, 1978.

Sterling, W.L. Economic Thresholds and Sampling of Heliothis Species in Cotton, Corn, Soybeans, and Other Host Plants. Bulletin 231, Southern Cooperative Series, 1979.

Stern, V.M. "Economic thresholds." Annual Review of Entomology. 18(1973):259-280.

----------. "The bionomics of pest control." Iowa State Journal of Research. 49(1975):467-472.

Stern, V.M., R.F. Smith, R. van den Bosch, and K.S. Hagen. "The integration of chemical and biological control of the spotted alfalfa aphid. I. The integrated control concept." Hilgardia. 29(1959):81-101.

Way, M.J. "Integrated control — practical realities." Outlook on Agriculture. 9(1977):127-135.

Way, M.J. and M.E. Cammell. "Constraints in establishing meaningful economic thresholds in relation to decision-making in pesticide application." EPPO Bulletin 10(1980):201-206.

Westigard, P.H., P.B. Lombard, and D.W. Berry. Integrated Pest Management of Insects and Mites Attacking Pears in Southern Oregon. Bulletin 634, Agricultural Experiment Station, Oregon State University, 1979.

Appendix A
LOSS FUNCTIONS USED IN THE SIMULATION ANALYSIS

The four loss functions used in this study provide alternative descriptions of the relationship between pest density and the mean and variance of crop loss. This appendix describes the relationships implied by these functions.

As the number of pests in a field increases, the resulting crop loss may increase proportionally, less than proportionally, or more than proportionally to the increase in number, implying that the expected effect per pest is constant, decreasing, or increasing. The linear loss functions in the study imply a constant mean effect per pest regardless of density. The exponential loss function implies an increasing mean effect per pest for the range of densities in the study. A decreasing effect per pest was not represented in the study, since the negative interactions that might produce a decreasing effect were assumed unlikely for the range of densities probable in commercial fields.

As the number of pests in a field increases, the variability in their combined effect also may change. The distribution of pests in the field and the manner in which the pests interact may determine the relationship between an increase in number of pests and the variability in their effect. For example, if loss caused by each pest varies identically and independently from the losses caused by all other pests in the field, and the variability σ_e^2 in the loss caused by any single pest does not depend on the density of pests (x) in the field, then the variance of their combined effect will be proportional to the number of pests in the field:

$$
\begin{aligned}
(1)\ \text{variance}(L{:}X{=}x) &= \text{var}\Big(\sum_{i=1}^{x} (g(x)+e_i)\Big) \\
&= \text{var}\Big(\sum_{i=1}^{x} e_i\Big) \\
&= \sum_{i=1}^{x} \text{var}(e_i) + 2 \sum\sum_{i<j} \text{cov}(e_i,e_j) \\
&= x\,\sigma_e^2 + 0 \\
&= x\,\sigma_e^2
\end{aligned}
$$

where L = loss for the field,

x = number of pests in the field,

$g(x)$ = expected loss per pest when the number of pests in the field is x (variance $(g(x)) = 0$; covariance$(g(x), e_i) = 0$ for each i),

e_i = random variability in loss caused by the i^{th} pest

(variance$(e_i) = \sigma_e^2$; covariance$(e_i, e_j) = 0$ for each i, $j \neq i$).

This model implies that the variability in loss among pests tends to average out, so the variance in loss per pest in the field decreases as the number of pests increases:

(2) $\text{var}(L/x) = x^{-2} \ \text{var}(L{:}X{=}x) = x^{-2}\,(x\,\sigma_e^2) = \sigma_e^2/x$

This model represents an averaging of the variability that might result from differences in feeding behavior within a population of pests. However, the assumed independence in effect among pests implies that the economic losses caused by two pests in the same field, or in the same season, are no more closely related than losses caused by two pests in two different fields and/or seasons. Since crop prices, crop variety, and weather will be the same for all pests in a field, the economic losses caused by these pests will be related, so the independence model seems inappropriate.

Another model for the variability in loss from pests is that each additional pest causes a loss identical to the loss caused by every other pest in the field (correlation coefficient for losses caused by any two pests = 1.0). With this model, an increase in the number of pests would increase more than proportionally the variance of the combined loss from all pests in the field:

$$
\begin{aligned}
\text{(3) variance}(L{:}X{=}x) &= \text{var}\Big(\sum_{i=1}^{x} (g(x) + u_i)\Big) \\
&= \text{var}\Big(\sum_{i=1}^{x} u_i\Big) \\
&= \sum_{i=1}^{x} \text{var}(u_i) + 2 \sum\sum_{i<j} \text{cov}(u_i, u_j) \\
&= x\,\sigma_u^2 \quad + x(x-1)\,\sigma_u^2 \\
&= x^2\,\sigma_u^2
\end{aligned}
$$

where L, x, and $g(x)$ are as previously defined, and

u_i = random variability in loss caused by the i^{th} pest

(variance$(u_i) = \sigma_u^2$; covariance$(u_i, u_j) = \sigma_u^2$ for each i, j).

This model implies that the variance in loss per pest in the field remains the same as the number of pests increases,

$$(4)\ \mathrm{var}(L/x) = x^{-2}\ \ \mathrm{var}(L{:}X{=}x) = \sigma_u^2$$

as expected since the loss from every pest in the field is identical, so variability is not averaged out. An identical loss for every pest in a field would occur when variability in the loss caused by pests results from factors shared by all pests in the field, such as price and variety of the crop, and weather. Although identical losses from all pests are unlikely, this model may be appropriate if the shared factors are predominant in determining loss.

A third model for the variability in loss from pests is that the variability in the combined loss from all pests in the field remains the same regardless of number of the pests in the field.

$$(5)\ \mathrm{variance}(L{:}X{=}x) = \mathrm{var}((\sum_{i=1}^{x} g(x)) + v)$$

$$= \mathrm{var}(v)$$

$$= \sigma_v^2$$

where L, x, and g(x) are as previously defined, and

v = random variability in combined loss for entire field

(variance(v)= σ_v^2)

This model implies that the interaction among pests stabilizes the loss caused by each one. As the number of pests increase, the loss per pest becomes less variable:

$$(6)\ \mathrm{var}(L/x) = x^{-2}\ \sigma_v^2$$

The rate at which variability in loss per pest decreases is x-times faster than the decrease in variability that occurs in the first model, for which the independent variability among pests in the field averages out, when

$$\sigma^2_e = \sigma^2_v$$

The variability terms specified for the loss functions in the study represent the two extremes of the three models described above. The additive variability term represents the third model, in which variance of total loss per acre is constant regardless of pest density. The multiplicative variability term is analogous to the second model, in which the loss from each pest is identical. The multiplicative variability term used in loss function LF3 results in:

$$(7)\ \text{variance}\ (L{:}X{=}x) = \text{var}(mxw_2)$$
$$= m^2\ x^2\ \text{var}(w_2)$$
$$= x^2\ m^2\ \sigma^2_{w2}$$

where L and x are as previously defined,

$m = g(x)$ = expected loss per pest (a constant in LF3), and

w_2 = random variability in combined loss for entire field

(variance(w_2)= σ^2_{w2})

A comparison of equations (3) and (7) indicates that the variances for the two models have the same relationship with pest density.

APPENDIX B
DERIVATION OF TRUE THRESHOLD FOR ALTERNATIVE LOSS AND COST FUNCTIONS

For the first specification of cost when pesticide was applied, that cost equaled a constant \$6. The threshold density was therefore the density that on average resulted in a loss equal to \$6. For both the linear and exponential loss functions a density of five pests per plant resulted in an average crop loss equal to \$6. Consequently, the true threshold density was five for the first specification of pesticide cost.

For the second specification of costs when pesticide was applied, the cost depended in part on the crop loss that would have occurred if the pesticide had not been applied. For this specification, the true threshold density can be calculated by identifying the pest density at which average crop loss without the pesticide application equaled average cost with the application. The average cost with pesticide application equaled \$4.20 plus the product of the mean value of the fraction F and the average crop loss for the pest density: average cost with pesticide = $E(K:X=x)$ = \$4.20 + $E(F)\ E(L:X=x)$ = \$4.20 + .3 $E(L:X=x)$. To find the density at which this average cost with pesticide equaled average crop loss without pesticide, the loss functions were used to calculate ($E(L:X=x)$ in terms of pest density and then crop loss was set equal to cost with pesticide. For the linear loss function, $E(L:X=x) = 1.2x$. At the threshold,

$$E(L:X=x) = E(K:X=x)$$

$$1.2x = 4.20 + .3(1.2x)$$

Solving for x indicates that the threshold density is five.

For the exponential loss function, $E(L:X=x) = \exp(.4238x - .006922x^2) - 1$. At the threshold,

$$\exp(.4238x - .006922x^2) - 1 = 4.20 + .3(\exp(.4238x - .006922x^2) -1)$$

$$(.7)(\exp(.4238x - .006922x^2) - 1) = 4.20$$

$$(.4238x - .006922x^2) = \ln(7).$$

Solving this quadratic for x indicates that the threshold density is again five for the relevant region of the loss function.

Appendix C
PROCEDURES USED TO GENERATE VALUES FOR RANDOM VARIABLES

For the 400 replications, 400 values from each of the gamma probability distributions were generated by first obtaining 400 values from the uniform distribution over the interval (0,1) using the GGUBS subroutine from the International Statistical and Mathematical Library (IMSL). The uniform values were transformed into values from the gamma distributions by the probability integral transformation (Mood, Graybill, and Boes, page 202). This transformation was performed with the Inverse Chi-Square IMSL subroutine MDCHI, followed by scaling to produce values from the desired gamma distribution.[8] Generating values for all five gamma distributions using the same uniform values reduced the sampling variability that could have obscured true differences in results among the gamma distributions if values from the different distributions were generated independently. The observed frequency distributions for each of the gamma distributions and statistics describing those distributions are presented in Figure C1.

The 400 values of the variability term for each of the loss functions were generated by first obtaining 400 values from the standard normal distribution (mean = 0, variance = 1) using the IMSL subroutine GGNML. The values of the variability terms for each loss function were then obtained by transforming these standard normal values. Values for the additive variability terms w_1 and $2w_1$ were derived by multiplying the standard normal values by the standard deviation of the additive term.

Values for the multiplicative variability term w_2 were generated in two steps. First, the standard normal values were transformed to values of $\ln(w_2)$, the natural log of the variability term. Since w_2 was specified to have a lognormal distribution with mean equal to one and variance equal to .583, the natural log of w_2 had a normal distribution with mean equal to -.230 and variance equal to .459 (Mood, Graybill, and Boes, page 117). Accordingly, the standard normal values were transformed into values for $\ln(w_2)$ by multiplying by sq.rt.(.459) and subtracting .230. Second, the values of $\ln(w_2)$ were transformed into values of w_2. As with the methods used to generate the gamma values, generating values for the three specifications of variability using the same standard normal values reduced sampling variability. The average of the 400 standard normal values was .039 and their sample variance was .915.

Sample counts for samples of size 30 and 60 were generated for each of the 400 pest densities from each of the five gamma frequency distributions. The counts were generated from the negative binomial distribution having mean equal to sample size times pest density and index of aggregation equal to sample size times .5. The IMSL subroutine GGBNR was used. The estimated pest densities averaged over the 400 observed values of each pest distribution are reported for both sample sizes in Figure C1.

For calculating pesticide cost that included fractional crop loss, 400 values of the variable fraction F were generated using the IMSL subroutine GGBTR. The average of the 400 F values was .313, the variance was .0318.

---

[8] The Inverse Chi-Square subroutine works for fractional degrees of freedom so the transformation could be accomplished for gamma distributions including those having shape parameters that were not integer multiples of 0.5.

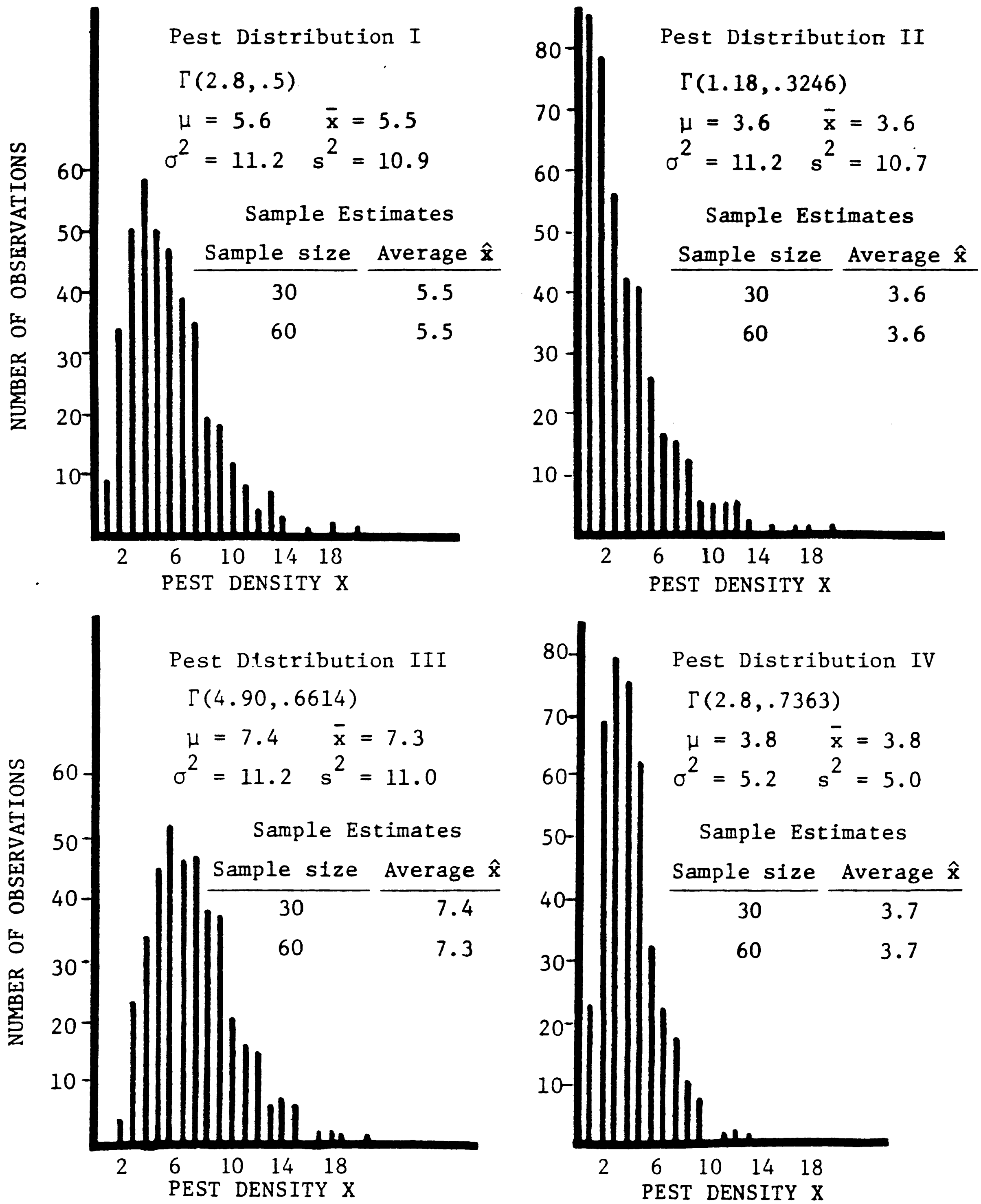


Figure C1. Frequency Distributions of Observed Pest Densities.

continued on next page

continued from previous page

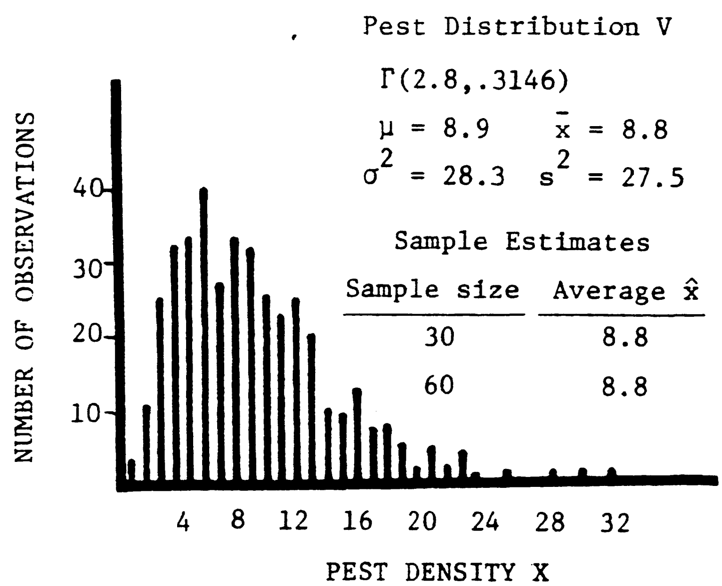


Figure C1. Frequency Distributions of Observed Pest Densities.

Appendix D

TABLES OF RESULTS

TABLE D.1:PERFORMANCE OF THRESHOLD T=5 COMPARED TO ROUTINE APPLICATIONS

NUMBER OF PLANTS INSPECTED = 30
NO LOSS WITH PESTICIDE

LOSS FUNCTION	IV	II	I	III	V
	FREQUENCY DISTRIBUTION				
	AVERAGE SAVINGS				
1	1.80	2.54	1.04	0.12	0.45
2	1.67	2.53	1.00	0.03	0.46
3	1.81	2.63	1.16	0.18	0.49
4	2.24	3.00	1.32	-0.18	0.55
	REDUCTION IN STANDARD DEVIATION				
1	-3.22	-3.36	-2.61	-1.94	-1.99
2	-5.55	-5.53	-4.41	-3.27	-3.37
3	-3.55	-2.90	-2.32	-2.25	-1.95
4	-5.78	-5.78	-4.61	-4.47	-3.70
	REDUCTION IN Q975				
1	-4	-4	-3	-5	-3
2	-9	-8	-8	-8	-7
3	-6	-4	-4	-6	-4
4	-9	-8	-7	-11	-7
	FREQUENCY OF PESTICIDE APPLICATIONS USING T=5				
	0.225	0.227	0.465	0.697	0.720

ENTRIES ARE THE STATISTIC FOR ROUTINE APPLICATIONS MINUS THE STATISTIC FOR THE THRESHOLD T=5

CONTINUED
TABLE D.1:PERFORMANCE OF THRESHOLD T=5 COMPARED TO NO APPLICATIONS

NUMBER OF PLANTS INSPECTED = 30
NO LOSS WITH PESTICIDE

	FREQUENCY DISTRIBUTION				
LOSS FUNCTION	IV	II	I	III	V
	AVERAGE SAVINGS				
1	0.42	0.94	1.79	3.04	5.11
2	0.41	1.04	1.87	3.07	5.24
3	0.46	1.08	2.01	3.23	5.38
4	1.84	5.82	10.13	18.07	48.32
	REDUCTION IN STANDARD DEVIATION				
1	0.81	1.60	2.38	3.07	5.03
2	0.97	1.61	2.76	3.91	5.35
3	1.88	3.70	5.68	7.16	10.77
4	4.69	21.98	25.17	32.27	92.99
	REDUCTION IN Q975				
1	4	7	9	9	19
2	4	7	9	12	17
3	10	11	23	24	42
4	16	46	72	103	355
	FREQUENCY OF PESTICIDE APPLICATIONS USING T=5				
	0.225	0.227	0.465	0.697	0.720

ENTRIES ARE THE STATISTIC FOR NO APPLICATIONS
MINUS THE STATISTIC FOR THE THRESHOLD T=5

CONTINUED
TABLE D.1:PERFORMANCE OF THRESHOLD T=5 COMPARED TO ROUTINE APPLICATIONS

NUMBER OF PLANTS INSPECTED = 30
VARIABLE LOSS WITH PESTICIDE

LOSS FUNCTION	FREQUENCY DISTRIBUTION IV	II	I	III	V
	AVERAGE SAVINGS				
1	1.33	1.82	0.78	0.09	0.33
2	1.27	1.83	0.76	0.02	0.33
3	1.35	1.87	0.86	0.13	0.36
4	1.67	2.15	0.98	-0.12	0.39
	REDUCTION IN STANDARD DEVIATION				
1	-1.79	-1.92	-1.22	-0.60	-0.64
2	-3.28	-3.29	-2.26	-1.25	-1.28
3	-1.84	-1.41	-0.82	-0.55	-0.43
4	-3.00	-1.88	-1.17	-0.58	-0.34
	REDUCTION IN Q975				
1	-1	-1	0	0	0
2	-3	-2	-1	-1	-1
3	-2	0	-1	-1	0
4	-1	0	0	0	0
	FREQUENCY OF PESTICIDE APPLICATIONS USING T=5				
	0.225	0.227	0.465	0.697	0.720

ENTRIES ARE THE STATISTIC FOR ROUTINE APPLICATIONS
MINUS THE STATISTIC FOR THE THRESHOLD T=5

CONTINUED
TABLE D.1:PERFORMANCE OF THRESHOLD T=5 COMPARED TO NO APPLICATIONS

NUMBER OF PLANTS INSPECTED = 30
VARIABLE LOSS WITH PESTICIDE

	FREQUENCY DISTRIBUTION				
LOSS FUNCTION	IV	II	I	III	V
	AVERAGE SAVINGS				
1	0.27	0.61	1.18	1.98	3.42
2	0.26	0.66	1.21	1.97	3.47
3	0.32	0.71	1.34	2.11	3.59
4	1.25	3.97	6.90	12.27	32.99
	REDUCTION IN STANDARD DEVIATION				
1	0.61	1.15	1.66	2.05	3.29
2	0.81	1.24	2.12	2.94	3.84
3	1.55	2.84	4.17	5.21	7.51
4	3.84	16.92	18.58	23.25	62.05
	REDUCTION IN Q975				
1	3	5	6	7	12
2	4	6	8	10	12
3	9	8	18	19	32
4	13	31	46	67	233
	FREQUENCY OF PESTICIDE APPLICATIONS USING T=5				
	0.225	0.227	0.465	0.697	0.720

ENTRIES ARE THE STATISTIC FOR NO APPLICATIONS
MINUS THE STATISTIC FOR THE THRESHOLD T=5

CONTINUED
TABLE D.1:PERFORMANCE OF THRESHOLD T=5 COMPARED TO ROUTINE APPLICATIONS

NUMBER OF PLANTS INSPECTED = 60
NO LOSS WITH PESTICIDE

	FREQUENCY DISTRIBUTION				
LOSS FUNCTION	IV	II	I	III	V
	AVERAGE SAVINGS				
1	1.90	2.55	1.09	0.36	0.51
2	1.83	2.50	1.05	0.37	0.54
3	1.93	2.54	1.09	0.35	0.50
4	2.45	3.04	1.45	0.51	0.71
	REDUCTION IN STANDARD DEVIATION				
1	-3.12	-3.36	-2.71	-1.94	-2.06
2	-5.39	-5.57	-4.65	-3.46	-3.53
3	-3.21	-4.15	-3.00	-2.17	-2.12
4	-5.59	-5.82	-4.86	-3.72	-3.77
	REDUCTION IN Q975				
1	-3	-2	-4	-3	-3
2	-8	-8	-9	-7	-8
3	-4	-2	-5	-5	-4
4	-8	-7	-7	-8	-7
FREQUENCY OF PESTICIDE APPLICATIONS USING T=5	0.260	0.235	0.470	0.712	0.710

ENTRIES ARE THE STATISTIC FOR ROUTINE APPLICATIONS
MINUS THE STATISTIC FOR THE THRESHOLD T=5

CONTINUED
TABLE D.1:PERFORMANCE OF THRESHOLD T=5 COMPARED TO
NO APPLICATIONS

NUMBER OF PLANTS INSPECTED = 60
NO LOSS WITH PESTICIDE

	FREQUENCY DISTRIBUTION				
LOSS FUNCTION	IV	II	I	III	V
	AVERAGE SAVINGS				
1	0.52	0.95	1.84	3.28	5.17
2	0.57	1.01	1.92	3.41	5.32
3	0.58	0.99	1.94	3.40	5.39
4	2.05	5.86	10.26	18.76	48.48
	REDUCTION IN STANDARD DEVIATION				
1	0.91	1.60	2.28	3.07	4.96
2	1.13	1.57	2.52	3.72	5.19
3	2.22	2.45	5.00	7.24	10.60
4	4.88	21.94	24.92	33.02	92.92
	REDUCTION IN Q975				
1	5	9	8	11	19
2	5	7	8	13	16
3	12	13	22	25	42
4	17	47	72	106	355
	FREQUENCY OF PESTICIDE APPLICATIONS USING T=5				
	0.260	0.235	0.470	0.712	0.710

ENTRIES ARE THE STATISTIC FOR NO APPLICATIONS
MINUS THE STATISTIC FOR THE THRESHOLD T=5

CONTINUED
TABLE D.1:PERFORMANCE OF THRESHOLD T=5 COMPARED TO NO APPLICATIONS

NUMBER OF PLANTS INSPECTED = 60
VARIABLE LOSS WITH PESTICIDE

LOSS FUNCTION	FREQUENCY DISTRIBUTION IV	II	I	III	V
	AVERAGE SAVINGS				
1	0.31	0.61	1.22	2.17	3.44
2	0.34	0.63	1.26	2.22	3.52
3	0.36	0.64	1.28	2.24	3.59
4	1.35	3.99	7.00	12.76	33.10
	REDUCTION IN STANDARD DEVIATION				
1	0.64	1.13	1.58	1.96	3.24
2	0.89	1.19	1.94	2.71	3.71
3	1.73	1.96	3.78	5.19	7.45
4	3.91	16.89	18.46	23.21	61.99
	REDUCTION IN Q975				
1	3	6	6	7	12
2	4	6	7	10	12
3	9	7	17	17	32
4	14	30	46	67	233
	FREQUENCY OF PESTICIDE APPLICATIONS USING T=5				
	0.260	0.235	0.470	0.712	0.710

ENTRIES ARE THE STATISTIC FOR NO APPLICATIONS
MINUS THE STATISTIC FOR THE THRESHOLD T=5

CONTINUED
TABLE D.1:PERFORMANCE OF THRESHOLD T=5 COMPARED TO ROUTINE APPLICATIONS

NUMBER OF PLANTS INSPECTED = 60
VARIABLE LOSS WITH PESTICIDE

LOSS FUNCTION	FREQUENCY DISTRIBUTION IV	II	I	III	V
	AVERAGE SAVINGS				
1	1.37	1.82	0.82	0.28	0.35
2	1.35	1.80	0.81	0.27	0.38
3	1.39	1.80	0.80	0.26	0.36
4	1.77	2.17	1.08	0.37	0.50
	REDUCTION IN STANDARD DEVIATION				
1	-1.76	-1.94	-1.30	-0.69	-0.69
2	-3.20	-3.34	-2.44	-1.48	-1.41
3	-1.66	-2.29	-1.21	-0.57	-0.49
4	-2.93	-1.91	-1.29	-0.62	-0.40
	REDUCTION IN Q975				
1	-1	0	0	0	0
2	-3	-2	-2	-1	-1
3	-2	-1	-2	-3	0
4	0	-1	0	0	0
	FREQUENCY OF PESTICIDE APPLICATIONS USING T=5				
	0.260	0.235	0.470	0.712	0.710

ENTRIES ARE THE STATISTIC FOR ROUTINE APPLICATIONS
MINUS THE STATISTIC FOR THE THRESHOLD T=5

TABLE D.2: VARIANCE AND .975 QUANTILE (Q975) OF THRESHOLD T=5 COMPARED TO THOSE OF THE OTHER THRESHOLDS

FREQUENCY DISTRIBUTION I NUMBER OF PLANTS INSPECTED= 30

RATIO OF VARIANCES (VARIANCE OF COST FOR THRESHOLD/VARIANCE OF COST FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE LOSS FUNCTION				VARIABLE LOSS WITH PESTICIDE LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	0.00	0.00	0.00	0.00	0.40	0.31	0.62	0.80
2.5	0.785	0.63	0.51	0.54	0.53	0.80	0.67	0.84	0.92
4.0	0.592	0.87	0.84	0.86	0.83	0.94	0.89	0.94	0.97
4.5	0.520	0.95	0.94	0.93	0.94	0.98	0.96	0.97	0.99
5.0	0.465	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5.5	0.385	1.16	1.20	1.73	1.21	1.08	1.13	1.23	1.03
6.0	0.327	1.27	1.31	1.96	1.40	1.13	1.20	1.31	1.05
7.5	0.232	1.56	1.54	3.36	2.10	1.24	1.34	1.70	1.13
10.0	0.125	2.40	2.07	7.07	6.13	1.62	1.65	2.84	1.66
∞	0.000	3.66	2.64	11.89	41.73	2.25	2.02	4.36	7.07
VARIANCE FOR T=5		6.81	19.45	5.38	21.25	11.09	25.50	14.67	125.44

DIFFERENCE IN Q975 (Q975 FOR THE THRESHOLD MINUS Q975 FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE LOSS FUNCTION				VARIABLE LOSS WITH PESTICIDE LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	-3.	-8.	-4.	-7.	0.	-1.	-1.	0.
2.5	0.785	-2.	-5.	-4.	-5.	0.	-1.	-1.	0.
4.0	0.592	0.	-2.	-1.	-1.	0.	0.	0.	0.
4.5	0.520	0.	-1.	-1.	0.	0.	0.	0.	0.
5.0	0.465	0.	0.	0.	0.	0.	0.	0.	0.
5.5	0.385	1.	0.	2.	2.	0.	0.	0.	0.
6.0	0.327	2.	1.	2.	4.	1.	1.	1.	0.
7.5	0.232	3.	2.	4.	8.	1.	1.	1.	3.
10.0	0.125	6.	5.	12.	29.	3.	4.	8.	12.
∞	0.000	9.	9.	23.	72.	6.	8.	18.	46.
Q975 FOR T=5		9.	14.	10.	13.	12.	15.	15.	39.

CONTINUED

TABLE D.2:VARIANCE AND .975 QUANTILE (Q975) OF THRESHOLD T=5 COMPARED TO THOSE OF THE OTHER THRESHOLDS

FREQUENCY DISTRIBUTION I NUMBER OF PLANTS INSPECTED= 60

RATIO OF VARIANCES (VARIANCE OF COST FOR THRESHOLD/VARIANCE OF COST FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE LOSS FUNCTION				VARIABLE LOSS WITH PESTICIDE LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	0.00	0.00	0.00	0.00	0.38	0.28	0.51	0.79
2.5	0.810	0.56	0.41	0.31	0.43	0.74	0.59	0.68	0.89
4.0	0.582	0.86	0.82	0.73	0.82	0.94	0.89	0.89	0.97
4.5	0.522	0.93	0.92	0.88	0.90	0.97	0.95	0.95	0.99
5.0	0.470	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5.5	0.420	1.06	1.05	1.05	1.08	1.02	1.03	1.01	1.01
6.0	0.362	1.15	1.13	1.17	1.23	1.06	1.08	1.07	1.02
7.5	0.247	1.52	1.42	2.09	2.17	1.23	1.27	1.43	1.15
10.0	0.095	2.24	1.88	5.09	4.83	1.54	1.54	2.65	1.50
∞	0.000	3.39	2.38	7.11	37.55	2.14	1.88	3.59	6.92
VARIANCE FOR T=5		7.34	21.62	9.00	23.62	11.63	27.35	17.81	128.14

DIFFERENCE IN Q975 (Q975 FOR THE THRESHOLD MINUS Q975 FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE LOSS FUNCTION				VARIABLE LOSS WITH PESTICIDE LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	-4.	-9.	-5.	-7.	0.	-2.	-2.	0.
2.5	0.810	-4.	-7.	-5.	-6.	0.	-2.	-2.	0.
4.0	0.582	-2.	-2.	-3.	-1.	0.	-1.	-1.	0.
4.5	0.522	-1.	-1.	-2.	0.	0.	-1.	-1.	0.
5.0	0.470	0.	0.	0.	0.	0.	0.	0.	0.
5.5	0.420	0.	0.	0.	2.	0.	0.	0.	0.
6.0	0.362	0.	0.	1.	3.	0.	0.	1.	0.
7.5	0.247	3.	1.	4.	10.	2.	1.	2.	6.
10.0	0.095	4.	4.	10.	27.	3.	3.	5.	6.
∞	0.000	8.	8.	22.	72.	6.	7.	17.	46.
Q975 FOR T=5		10.	15.	11.	13.	12.	16.	16.	39.

CONTINUED

TABLE D.2: VARIANCE AND .975 QUANTILE (Q975) OF THRESHOLD T=5 COMPARED TO THOSE OF THE OTHER THRESHOLDS

FREQUENCY DISTRIBUTION II NUMBER OF PLANTS INSPECTED= 30

RATIO OF VARIANCES (VARIANCE OF COST FOR THRESHOLD/VARIANCE OF COST FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE LOSS FUNCTION				VARIABLE LOSS WITH PESTICIDE LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	0.00	0.00	0.00	0.00	0.25	0.20	0.39	0.68
2.5	0.507	0.86	0.71	0.76	0.69	0.88	0.77	0.85	0.91
4.0	0.322	0.93	0.91	0.93	0.87	0.95	0.93	0.96	0.97
4.5	0.277	0.95	0.95	0.93	0.93	0.98	0.96	0.97	0.98
5.0	0.227	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5.5	0.205	1.05	1.04	1.11	1.08	1.03	1.03	1.06	1.02
6.0	0.170	1.10	1.10	1.46	1.21	1.06	1.07	1.24	1.04
7.5	0.112	1.26	1.20	1.81	1.65	1.13	1.13	1.36	1.12
10.0	0.063	1.46	1.36	3.82	2.15	1.26	1.24	2.40	1.24
∞	0.000	2.18	1.67	5.18	23.07	1.69	1.46	3.08	6.56
VARIANCE FOR T=5		11.29	30.58	8.41	33.41	14.52	34.81	14.14	117.51

DIFFERENCE IN Q975 (Q975 FOR THE THRESHOLD MINUS Q975 FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE LOSS FUNCTION				VARIABLE LOSS WITH PESTICIDE LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	-4.	-8.	-4.	-8.	-1.	-2.	0.	0.
2.5	0.507	-3.	-3.	-4.	-4.	-1.	-2.	0.	0.
4.0	0.322	-2.	-1.	-2.	-2.	0.	0.	1.	0.
4.5	0.277	-1.	-1.	-2.	-1.	0.	0.	1.	0.
5.0	0.227	0.	0.	0.	0.	0.	0.	0.	0.
5.5	0.205	0.	0.	1.	2.	0.	0.	1.	0.
6.0	0.170	1.	1.	3.	4.	0.	1.	2.	0.
7.5	0.112	2.	2.	4.	7.	0.	1.	2.	6.
10.0	0.063	3.	2.	5.	11.	2.	1.	3.	9.
∞	0.000	7.	7.	11.	46.	5.	6.	8.	31.
Q975 FOR T=5		10.	14.	10.	14.	12.	15.	13.	29.

CONTINUED

TABLE D.2: VARIANCE AND .975 QUANTILE (Q975) OF THRESHOLD T=5 COMPARED TO THOSE OF THE OTHER THRESHOLDS

FREQUENCY DISTRIBUTION II NUMBER OF PLANTS INSPECTED= 60

RATIO OF VARIANCES (VARIANCE OF COST FOR THRESHOLD/VARIANCE OF COST FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE				VARIABLE LOSS WITH PESTICIDE			
		LOSS FUNCTION				LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	0.00	0.00	0.00	0.00	0.24	0.19	0.26	0.68
2.5	0.537	0.83	0.68	0.36	0.65	0.85	0.73	0.55	0.89
4.0	0.342	0.89	0.84	0.39	0.80	0.92	0.87	0.59	0.95
4.5	0.290	0.92	0.90	0.43	0.85	0.95	0.92	0.63	0.96
5.0	0.235	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5.5	0.200	1.04	1.04	1.02	1.06	1.02	1.03	1.01	1.01
6.0	0.180	1.10	1.10	1.20	1.16	1.04	1.06	1.11	1.03
7.5	0.112	1.23	1.21	1.42	1.35	1.10	1.12	1.25	1.07
10.0	0.070	1.38	1.28	1.50	1.85	1.19	1.18	1.30	1.17
∞	0.000	2.18	1.64	2.53	22.75	1.68	1.44	2.02	6.52
VARIANCE FOR T=5		11.29	31.02	17.22	33.87	14.67	35.40	21.53	118.16

DIFFERENCE IN Q975 (Q975 FOR THE THRESHOLD MINUS Q975 FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE				VARIABLE LOSS WITH PESTICIDE			
		LOSS FUNCTION				LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	-2.	-8.	-2.	-7.	0.	-2.	-1.	-1.
2.5	0.537	-1.	-3.	-2.	-3.	0.	-1.	-1.	-1.
4.0	0.342	0.	-2.	-1.	-2.	0.	-1.	-1.	-1.
4.5	0.290	0.	-2.	0.	-1.	0.	-1.	-1.	-1.
5.0	0.235	0.	0.	0.	0.	0.	0.	0.	0.
5.5	0.200	1.	0.	1.	0.	1.	0.	0.	0.
6.0	0.180	2.	0.	3.	2.	1.	0.	0.	0.
7.5	0.112	3.	1.	6.	6.	1.	0.	0.	0.
10.0	0.070	4.	2.	6.	11.	1.	1.	1.	6.
∞	0.000	9.	7.	13.	47.	6.	6.	7.	30.
Q975 FOR T=5		8.	14.	8.	13.	11.	15.	14.	30.

CONTINUED

TABLE D.2: VARIANCE AND .975 QUANTILE (Q975) OF THRESHOLD T=5 COMPARED TO THOSE OF THE OTHER THRESHOLDS

FREQUENCY DISTRIBUTION III   NUMBER OF PLANTS INSPECTED= 30

RATIO OF VARIANCES (VARIANCE OF COST FOR THRESHOLD/VARIANCE OF COST FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE LOSS FUNCTION				VARIABLE LOSS WITH PESTICIDE LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	0.00	0.00	0.00	0.00	0.64	0.50	0.76	0.92
2.5	0.947	0.26	0.22	0.14	0.14	0.77	0.63	0.81	0.94
4.0	0.820	0.62	0.65	0.62	0.40	0.89	0.85	0.93	0.96
4.5	0.752	0.77	0.80	0.71	0.55	0.94	0.92	0.95	0.97
5.0	0.697	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5.5	0.630	1.35	1.39	1.67	1.32	1.11	1.20	1.15	1.03
6.0	0.585	1.53	1.56	1.81	1.75	1.16	1.28	1.17	1.05
7.5	0.405	2.42	2.34	4.09	3.29	1.40	1.64	1.73	1.14
10.0	0.202	3.86	3.28	9.62	10.54	1.80	2.06	3.01	1.72
∞	0.000	6.67	4.82	17.49	67.56	2.86	2.87	5.02	7.42
VARIANCE FOR T=5		3.76	10.69	5.06	19.98	8.76	17.98	17.64	181.98

DIFFERENCE IN Q975 (Q975 FOR THE THRESHOLD MINUS Q975 FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE LOSS FUNCTION				VARIABLE LOSS WITH PESTICIDE LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	-5.	-8.	-6.	-11.	0.	-1.	-1.	0.
2.5	0.947	-5.	-8.	-6.	-11.	0.	-1.	-1.	0.
4.0	0.820	-2.	-1.	-3.	-4.	0.	0.	0.	0.
4.5	0.752	-1.	-1.	-2.	-3.	0.	0.	0.	0.
5.0	0.697	0.	0.	0.	0.	0.	0.	0.	0.
5.5	0.630	1.	2.	2.	3.	0.	1.	2.	0.
6.0	0.585	1.	2.	2.	4.	0.	1.	2.	2.
7.5	0.405	2.	3.	5.	14.	1.	2.	4.	2.
10.0	0.202	5.	5.	9.	36.	3.	3.	5.	17.
∞	0.000	9.	12.	24.	103.	7.	10.	19.	67.
Q975 FOR T=5		11.	14.	12.	17.	13.	16.	17.	53.

CONTINUED

TABLE D.2: VARIANCE AND .975 QUANTILE (Q975) OF THRESHOLD T=5 COMPARED TO THOSE OF THE OTHER THRESHOLDS

FREQUENCY DISTRIBUTION III NUMBER OF PLANTS INSPECTED= 60

RATIO OF VARIANCES (VARIANCE OF COST FOR THRESHOLD/VARIANCE OF COST FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE				VARIABLE LOSS WITH PESTICIDE			
		LOSS FUNCTION				LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	0.00	0.00	0.00	0.00	0.60	0.45	0.75	0.91
2.5	0.947	0.26	0.21	0.16	0.20	0.71	0.57	0.80	0.93
4.0	0.847	0.63	0.57	0.39	0.57	0.89	0.79	0.88	0.98
4.5	0.780	0.75	0.71	0.56	0.70	0.93	0.86	0.92	0.99
5.0	0.712	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5.5	0.645	1.22	1.18	1.39	1.37	1.05	1.08	1.08	1.01
6.0	0.592	1.37	1.32	1.54	1.64	1.06	1.13	1.10	1.02
7.5	0.422	1.99	1.76	2.23	3.60	1.18	1.31	1.21	1.09
10.0	0.192	3.68	2.86	8.14	12.27	1.64	1.81	2.51	1.53
∞	0.000	6.67	4.31	18.80	97.54	2.70	2.58	4.97	7.37
VARIANCE FOR T=5		3.76	11.97	4.71	13.84	9.30	19.98	17.81	183.06

DIFFERENCE IN Q975 (Q975 FOR THE THRESHOLD MINUS Q975 FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE				VARIABLE LOSS WITH PESTICIDE			
		LOSS FUNCTION				LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	-3.	-7.	-5.	-8.	0.	-1.	-3.	0.
2.5	0.947	-3.	-7.	-5.	-8.	0.	-1.	-3.	0.
4.0	0.847	-2.	-4.	-5.	-6.	0.	-1.	-3.	0.
4.5	0.780	-1.	-3.	-4.	-4.	0.	0.	-2.	0.
5.0	0.712	0.	0.	0.	0.	0.	0.	0.	0.
5.5	0.645	1.	1.	1.	2.	0.	1.	0.	0.
6.0	0.592	2.	2.	2.	2.	0.	1.	0.	0.
7.5	0.422	3.	3.	5.	11.	1.	1.	0.	2.
10.0	0.192	7.	7.	11.	39.	3.	4.	5.	11.
∞	0.000	11.	13.	25.	106.	7.	10.	17.	67.
Q975 FOR T=5		9.	13.	11.	14.	13.	16.	19.	53.

CONTINUED

TABLE D.2: VARIANCE AND .975 QUANTILE (Q975) OF THRESHOLD T=5 COMPARED TO THOSE OF THE OTHER THRESHOLDS

FREQUENCY DISTRIBUTION IV NUMBER OF PLANTS INSPECTED= 30

RATIO OF VARIANCES (VARIANCE OF COST FOR THRESHOLD/VARIANCE OF COST FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE LOSS FUNCTION				VARIABLE LOSS WITH PESTICIDE LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	0.00	0.00	0.00	0.00	0.23	0.18	0.28	0.30
2.5	0.645	0.66	0.51	0.35	0.53	0.76	0.62	0.55	0.68
4.0	0.375	0.83	0.79	0.54	0.78	0.90	0.85	0.70	0.87
4.5	0.305	0.90	0.87	0.74	0.87	0.94	0.91	0.85	0.93
5.0	0.225	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5.5	0.190	1.01	1.01	1.00	1.02	1.01	1.02	1.01	1.02
6.0	0.150	1.03	1.04	1.01	1.07	1.02	1.04	1.01	1.05
7.5	0.080	1.11	1.11	1.07	1.21	1.07	1.09	1.05	1.13
10.0	0.025	1.36	1.26	1.65	1.97	1.23	1.21	1.48	1.61
∞	0.000	1.57	1.38	2.34	3.28	1.39	1.30	1.96	2.49
VARIANCE FOR T=5		10.37	30.80	12.60	33.41	11.70	32.60	15.05	43.96

DIFFERENCE IN Q975 (Q975 FOR THE THRESHOLD MINUS Q975 FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE LOSS FUNCTION				VARIABLE LOSS WITH PESTICIDE LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	-4.	-9.	-6.	-9.	-1.	-3.	-2.	-1.
2.5	0.645	-3.	-4.	-6.	-5.	-1.	-3.	-2.	-1.
4.0	0.375	-1.	-2.	-4.	-3.	0.	-1.	-1.	-1.
4.5	0.305	-1.	-1.	-3.	-1.	0.	0.	-1.	-1.
5.0	0.225	0.	0.	0.	0.	0.	0.	0.	0.
5.5	0.190	0.	0.	0.	0.	0.	0.	0.	0.
6.0	0.150	0.	0.	0.	1.	0.	0.	0.	0.
7.5	0.080	1.	0.	0.	2.	0.	0.	1.	1.
10.0	0.025	2.	1.	4.	9.	1.	1.	4.	8.
∞	0.000	4.	4.	10.	16.	3.	4.	9.	13.
Q975 FOR T=5		10.	15.	12.	15.	11.	15.	13.	18.

CONTINUED

TABLE D.2: VARIANCE AND .975 QUANTILE (Q975) OF THRESHOLD T=5 COMPARED TO THOSE OF THE OTHER THRESHOLDS

FREQUENCY DISTRIBUTION IV NUMBER OF PLANTS INSPECTED= 60

RATIO OF VARIANCES (VARIANCE OF COST FOR THRESHOLD/VARIANCE OF COST FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE LOSS FUNCTION				VARIABLE LOSS WITH PESTICIDE LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	0.00	0.00	0.00	0.00	0.23	0.19	0.30	0.31
2.5	0.647	0.72	0.56	0.45	0.58	0.78	0.65	0.61	0.71
4.0	0.392	0.86	0.82	0.55	0.81	0.90	0.86	0.70	0.88
4.5	0.320	0.95	0.94	0.91	0.92	0.96	0.94	0.93	0.94
5.0	0.260	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5.5	0.195	1.11	1.11	1.36	1.15	1.05	1.07	1.19	1.07
6.0	0.145	1.23	1.22	2.06	1.31	1.13	1.15	1.61	1.16
7.5	0.065	1.32	1.29	2.13	1.55	1.17	1.19	1.64	1.28
10.0	0.025	1.48	1.37	2.37	2.01	1.28	1.26	1.80	1.57
∞	0.000	1.67	1.46	2.86	3.51	1.41	1.34	2.15	2.55
VARIANCE FOR T=5		9.73	29.05	10.30	31.25	11.49	31.70	13.69	43.03

DIFFERENCE IN Q975 (Q975 FOR THE THRESHOLD MINUS Q975 FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE LOSS FUNCTION				VARIABLE LOSS WITH PESTICIDE LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	-3.	-8.	-4.	-8.	-1.	-3.	-2.	0.
2.5	0.647	-2.	-3.	-4.	-4.	-1.	-2.	-2.	0.
4.0	0.392	-1.	-1.	-2.	-2.	-1.	-2.	-2.	0.
4.5	0.320	0.	0.	-2.	-1.	0.	0.	-1.	0.
5.0	0.260	0.	0.	0.	0.	0.	0.	0.	0.
5.5	0.195	1.	1.	3.	1.	0.	0.	1.	2.
6.0	0.145	2.	2.	5.	3.	1.	1.	2.	3.
7.5	0.065	3.	2.	5.	6.	1.	1.	2.	4.
10.0	0.025	4.	2.	6.	10.	2.	1.	3.	9.
∞	0.000	5.	5.	12.	17.	3.	4.	9.	14.
Q975 FOR T=5		9.	14.	10.	14.	11.	15.	13.	17.

CONTINUED

TABLE D.2: VARIANCE AND .975 QUANTILE (Q975) OF THRESHOLD T=5 COMPARED TO THOSE OF THE OTHER THRESHOLDS

FREQUENCY DISTRIBUTION V NUMBER OF PLANTS INSPECTED= 30

RATIO OF VARIANCES (VARIANCE OF COST FOR THRESHOLD/VARIANCE OF COST FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE LOSS FUNCTION				VARIABLE LOSS WITH PESTICIDE LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	0.00	0.00	0.00	0.00	0.69	0.54	0.84	0.98
2.5	0.930	0.43	0.32	0.31	0.32	0.85	0.71	0.91	0.99
4.0	0.800	0.73	0.69	0.77	0.65	0.92	0.85	0.97	0.99
4.5	0.752	0.89	0.90	0.90	0.85	0.97	0.95	0.98	1.00
5.0	0.720	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5.5	0.700	1.08	1.10	1.30	1.10	1.01	1.04	1.03	1.00
6.0	0.650	1.37	1.38	2.49	1.59	1.05	1.13	1.14	1.00
7.5	0.500	2.09	1.87	3.52	5.06	1.16	1.29	1.24	1.01
10.0	0.320	3.90	2.86	8.88	33.17	1.45	1.59	1.75	1.21
∞	0.000	12.44	6.70	42.55	682.90	3.54	3.19	5.96	7.79
VARIANCE FOR T=5		3.96	11.36	3.80	13.69	13.91	23.81	27.14	1199.93

DIFFERENCE IN Q975 (Q975 FOR THE THRESHOLD MINUS Q975 FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE LOSS FUNCTION				VARIABLE LOSS WITH PESTICIDE LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	-3.	-7.	-4.	-7.	0.	-1.	0.	0.
2.5	0.930	-3.	-7.	-4.	-7.	0.	-1.	0.	0.
4.0	0.800	0.	-1.	-1.	-1.	0.	0.	0.	0.
4.5	0.752	0.	0.	-1.	0.	0.	0.	0.	0.
5.0	0.720	0.	0.	0.	0.	0.	0.	0.	0.
5.5	0.700	1.	1.	0.	2.	0.	0.	1.	0.
6.0	0.650	2.	2.	3.	4.	0.	0.	1.	0.
7.5	0.500	4.	4.	7.	15.	0.	1.	3.	0.
10.0	0.320	8.	6.	10.	52.	2.	3.	4.	30.
∞	0.000	19.	17.	42.	355.	12.	12.	32.	233.
Q975 FOR T=5		9.	13.	10.	13.	16.	18.	20.	135.

CONTINUED

TABLE D.2: VARIANCE AND .975 QUANTILE (Q975) OF THRESHOLD T=5 COMPARED TO THOSE OF THE OTHER THRESHOLDS

FREQUENCY DISTRIBUTION V   NUMBER OF PLANTS INSPECTED= 60

RATIO OF VARIANCES   (VARIANCE OF COST FOR THRESHOLD/VARIANCE OF COST FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE				VARIABLE LOSS WITH PESTICIDE			
		LOSS FUNCTION				LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	0.00	0.00	0.00	0.00	0.67	0.52	0.82	0.98
2.5	0.915	0.48	0.37	0.31	0.39	0.86	0.72	0.90	0.99
4.0	0.802	0.76	0.69	0.64	0.70	0.95	0.87	0.95	1.00
4.5	0.755	0.89	0.85	0.88	0.87	0.97	0.93	0.98	1.00
5.0	0.710	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5.5	0.675	1.11	1.12	1.15	1.19	1.01	1.04	1.01	1.00
6.0	0.625	1.24	1.23	1.34	1.37	1.02	1.06	1.03	1.00
7.5	0.522	1.62	1.53	2.02	2.25	1.07	1.17	1.11	0.99
10.0	0.357	2.72	2.17	4.04	8.92	1.23	1.37	1.32	1.01
∞	0.000	11.61	6.10	36.00	657.78	3.45	3.03	5.83	7.76
VARIANCE FOR T=5		4.24	12.46	4.49	14.21	14.29	25.10	27.77	1204.09

DIFFERENCE IN Q975   (Q975 FOR THE THRESHOLD MINUS Q975 FOR THRESHOLD T=5)

		NO LOSS WITH PESTICIDE				VARIABLE LOSS WITH PESTICIDE			
		LOSS FUNCTION				LOSS FUNCTION			
THRESHOLD	PESTICIDE FREQ	1	2	3	4	1	2	3	4
0.0	1.000	-3.	-8.	-4.	-7.	0.	-1.	0.	0.
2.5	0.915	-3.	-8.	-4.	-7.	0.	-1.	0.	0.
4.0	0.802	-2.	-5.	-4.	-5.	0.	-1.	0.	0.
4.5	0.755	0.	-1.	0.	0.	0.	0.	0.	0.
5.0	0.710	0.	0.	0.	0.	0.	0.	0.	0.
5.5	0.675	1.	0.	2.	2.	0.	0.	0.	0.
6.0	0.625	1.	0.	2.	3.	0.	0.	0.	0.
7.5	0.522	3.	2.	4.	7.	0.	0.	3.	0.
10.0	0.357	5.	4.	9.	32.	0.	2.	3.	0.
∞	0.000	19.	16.	42.	355.	12.	12.	32.	233.
Q975 FOR T=5		9.	14.	10.	13.	16.	18.	20.	135.